Institute of Polar Studies
Report No. 36

Glaciological Investigations on the Casement Glacier, Southeast Alaska

by

Donald N. Peterson
Institute of Polar Studies

September, 1970

The Ohio State University
Research Foundation
Columbus, Ohio 43212

INSTITUTE OF POLAR STUDIES

Report No. 36

GLACIOLOGICAL INVESTIGATIONS ON THE CASEMENT GLACIER, SOUTHEAST ALASKA

by

Donald N. Peterson

Institute of Polar Studies

July 1970

The Ohio State University
Research Foundation
Columbus, Ohio 43212

ABSTRACT

Measurements made on Casement Glacier during the summers of 1965, 1966, and 1967 revealed time-variations in the horizontal component of the surface velocities. The summer velocities were greater than the "winter" velocities. The magnitude of the summer velocities varied from year to year, but was always greater than the winter velocity. These changes in surface velocity correspond to changes in the basal sliding velocity as measured in an ice tunnel along the margin of the glacier.

The mass budget of the glacier for the glaciological year 1966-1967 was determined to be $-235 \pm 46 \times 10^9$ kg. Discharge and budget measurements were calculated for two sections of the glacier, between lines 2 and 3, and between lines 8 and lines 9, 11, 12, and 13 (Fig. 3). The mass budget of each section was negative, being -8.4×10^9 kg and -9.1×10^9 kg, respectively.

Englacial velocities were calculated at each of the stakes for which the ice thickness had been determined by gravity and the surface velocity by surveying. Using these velocity data, the vertical components of the surface velocity, the longitudinal ice thickness profile, the trajectory of a layer of ice was calculated from line 14 through line 2. The estimated travel-time for this motion would be approximately 140 years.

Two short-term heat-balance studies, of four days duration each, were conducted on the glacier in 1967. The contribution of each component of the heat balance equation was computed, first, using the assumption that the variation of the wind speed, temperature, and vapor pressure follows the power law, and later, recalculated assuming a logarithmic variation. The calculated results were compared with the observed values of the ablation during the corresponding periods. The values determined by the power law fit the observed ablation data better than those calculated from the logarithmic law. For the two studies, the relative contributions of Q_R (radiation), Q_A (sensible heat), Q_L latent heat), and Q_P (heat from rainwater) were 65, 19, 15 and 1 per cent, respectively.

Investigations were made in an ice tunnel on the variations in slip rate and the mechanics of basal sliding. Basal sliding at the point of observation in the tunnel was a continuous process; there was no jerky, stick-slip movement and any observed jerky movement on the surface probably resulted from fracture and shearing of the surface ice. The rate of sliding is affected by changes in the quantity of lubricating water at the bed and most of the observed annual, seasonal, and diurnal changes in surface velocity result from changes in the quantity of free water at the bed of the glacier. Artificial obstacles were placed on a bedrock knob and the mode of flow of ice around them examined.

It was determined that the critical size at which the contribution of regelation slip equals that of plastic flow is between 1 and 2.5 cm.

ACKNOWLEDGMENTS

This study of the Casement Glacier was funded by the U. S. Atomic Energy Commission, Contract No. AT(11-1)-1473 and was administered by The Ohio State University Research Foundation as Projects 2017 and 2017-A.

This project would not have been possible were it not for the initial planning and organization of Dr. Richard P. Goldthwait who was responsible for writing the original proposal. His visits in the field and his suggestions and encouragement were greatly appreciated by the writer.

The writer is especially grateful to his numerous field assistants who usually performed admirably, often making what were to them unexciting and laborious observations under the most adverse of conditions. They were John Lindsay, Mark Owens, Paul Hooge, and Peter Darvall in 1965; Mikkel Mandt, Gerald Holdsworth, Fredrick Erdmann, Thomas Sanders, and James Carroll in 1966; and Thomas Croley, Daniel Goodman, Peter Meisler, John Moravek and James States in 1967. Theodore Merrell, Paul Cress, and Robert Ellis also assisted in the field for a few weeks each in 1967. Thanks are also due to Garry McKenzie and his assistants who were conducting an independent study at Adams Inlet; they aided in the Casement field work during several visits to the camp.

The U. S. National Park Service personnel provided logistic support for the party during the three field seasons, for which the writer is grateful, especially the transportation to and from the field on the Park Service Motor Vessel <u>Nunatak</u>. Captain Jim Sanders of the <u>Nunatak</u> and his crew were always generous with their time and assistance in the tiresome task of loading and unloading equipment and supplies each summer. Messrs. Charles Janda, Ted Sullivan, Robert Howe, William Locke, Miss June Branner, and many others from the Glacier Bay headquarters contributed to the success of the field program.

Special thanks go to Dr. Garry McKenzie for the many hours of discussion both in the field and back in the office concerning the problems and results of the Casement Glacier study and to Dr. Čedomir Marangunić for sharing with the writer not only his ideas in discussion, but also several computer programs for the reduction of data which saved the writer countless hours.

Mr. Herbert Mehrling was responsible for the preparation and packing of equipment and assisted the writer with other logistics problems prior to leaving Columbus for the field each summer.

This manuscript was reviewed and revised by Dr. Colin B. B. Bull, Dr. Richard P. Goldthwait, Dr. Robert J. Fleck, and Dr. Garry D. McKenzie. Special thanks go to Dr. Bull and Dr. Arthur Mirsky of the Institute of Polar Studies, who spent many hours helping with the logistics and the preparation of the annual reports and proposals.

CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

CHAPTER I

INTRODUCTION

Location of the Field Studies

The field studies described in this report were conducted on Casement Glacier, which is northeast of Muir Inlet in Glacier Bay National Monument, southeast Alaska (58°57' N, 135°57' W) (Figure 1). The Casement Glacier system has an area of about 200 km^2 with névé basins at elevations between 1200 and 1700 m. The terminus, which is presently at an elevation of 60 m, is located 6.7 km northeast of Muir Inlet, where at the beginning of the present century it joined Muir Glacier (Figure 2).

Glacial History of the Region

The glacial history of Muir Inlet has been studied intensively by members of the Institute of Polar Studies, The Ohio State University (Goldthwait, 1963; Taylor, 1962; Price, 1964; Haselton, 1966; Goldthwait and others, 1966; McKenzie, 1970). The sequence of events from late Wisconsin time to present is fairly well understood and can be summarized as follows:

1. Before 10,400 years B.P. the ice fronts in Muir Inlet had retreated at least as far back as their present positions. Although no outwash gravels from this recession have been found, marine deposits, the Forest Creek Formation, accumulated in Muir Inlet.

2. About 10,400 years ago, the ice may have readvanced depositing what Haselton (1966) has called the Muir Till. The extent of this advance and the validity of the Muir Till has been questioned by McKenzie (1970). The feature on which Haselton based his suggestion may have been a local advance of Casement Glacier only.

3. About 7,500 years ago the climate warmed, resulting in the retreat of the ice fronts past their present terminal positions. Tree stumps of 7,000-2,000 years B.P. have been recovered from beneath the present-day retreating ice fronts. This warm interval (called the Hypsithermal) lasted about 5,000 years during which Muir Inlet and its tributaries were filled to sea level with outwash (Goldthwait, 1963).

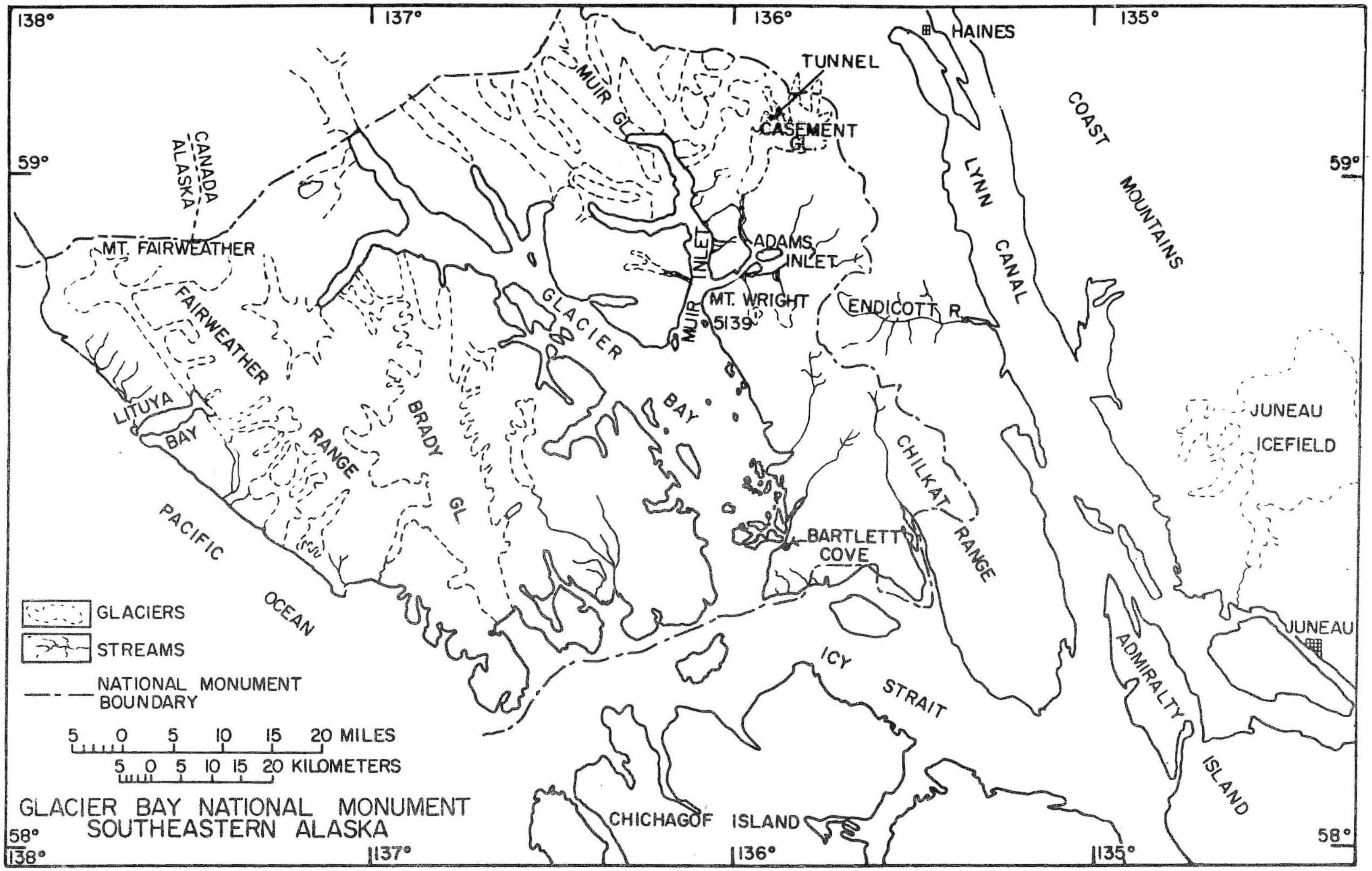


Fig. 1 - Map of Glacier Bay National Monument, southeast Alaska showing location of Casement Glacier.

Fig. 2 - Map of Muir Inlet area showing the retreat of the ice front of Muir, Casement, and associated glaciers at 10-year intervals since 1880. The contour interval on the topography is 500 ft. (from Goldthwait and others, 1966).

4. At the beginning of Neoglacial time (2,700 years B.P.) the ice front started to advance again. The date of the advance of the ice front past given points has been determined by radiometric age determinations on samples of wood from trees that were over-ridden. A sample from a log near the present front of Casement Glacier gives an age of 1,400 ± 120 years B.P. (Haselton, 1966). During Neoglacial time, the glaciers from Muir Inlet oscillated repeatedly. The maximum extent, reached about 300 years ago, is marked by a large terminal moraine just south of Bartlett Cove (Fig. 1).

5. Since the first recorded sighting in 1794 (Vancouver, 1801), the ice front in Glacier Bay has retreated about 75 km, approximately 15 times faster than most other retreating North American glaciers (Lawrence, 1958).

6. As the ice fronts retreat, flora and fauna re-establish themselves on the deglaciated land in a sequence determined by a field party from the Institute of Polar Studies (Goldthwait and others, 1966). Outwash streams are once again filling the arms of Muir Inlet, this time with post-Little Ice Age deposits.

Retreat of Casement Glacier

The earliest published map of Casement Glacier (Wright, 1887), shows the glacier to have been confluent with Muir and Adams Glaciers, with an ice thickness of about 300 m near the present shore line of Muir Inlet. Between 1892, the time of the first detailed map of Muir Inlet (Reid, 1896), and 1907, when another map was made by the International Boundary Commission, Muir Glacier retreated 13 km. By 1911 Casement Glacier had become separated from the retreating ice cliff and ended on land. A number of photographs showing the position of the terminus are available from that time to the present (Martin, 1911; U. S. Navy, 1929; Wright, 1931; Field, 1941; U.S.C.G.S., 1946 and 1948; Loken, 1956 and 1958; Price, 1962 and 1963; Post, 1965). Figure 2 shows the position of the terminus of Casement Glacier at 10-year intervals since 1880. Golthwait (1966) gives the annual rate of retreat as 30, 95, 98, 113, and 24 m/yr in successive decades from 1910 to 1960. However, because of areas of stagnant ice, proglacial lakes, proglacial drainage, and other reasons, the rate of retreat varies from point to point, and at some points it may be double that for others during the same interval.

Objectives of the Study

As can be seen in the section on the glacial history of the region, the retreat of the glaciers in the Muir Inlet area is well documented. One of the most important problems which remained was to determine the causes of this retreat, by assessing the mass and heat balances of a representative glacier in the area. Consequently, a three-year program was begun in the summer of 1965, the objectives of the study listed in the original proposal being as follows:

1. To assess the mass balance of the glacier by measurement of the annual accumulation in the névé basin, ablation over the length of the glacier, and the surface velocity at a number of points on transverse lines across the glacier.

2. To determine velocity profiles by measuring the variation with time of the inclination of holes drilled to the bottom of the glacier at a number of points in both the ablation and the accumulation areas.

3. To examine the ice near the bottom of the glacier, as exposed in the walls of a tunnel, to gain information on the mechanism of movement of the glacier on its bed.

4. To study the hydrology of water in the ice and on the outwash beyond the ice by the saline dispersal method.

5. To establish meteorological stations at various elevations on the glacier and at points on the rock adjacent to the glacier and to carry out detailed micrometeorological studies.

As a result of difficulties encountered in the field, the original program was altered so as to derive the maximum data which might be valuable in the study. However, all of the topics will be discussed in this report so that future investigators may avoid the problems encountered by the writer.

In addition to the original objectives, a number of secondary objectives were developed. Among them were:

1. Measurement of the ice thickness by gravimetric methods.

2. Evaluation of the relative contributions of each component in the heat balance equation.

3. Precise measurement of basal sliding rates in the ice tunnel to determine if the basal slip process is continuous or intermittent and to determine if there is any diurnal variation in slip rate.

4. Observation of the mode of flow of ice around obstacles placed on one bedrock knob exposed in a tunnel under the glacier.

Selection of the Glacier

Because it is not physically possible to study all of the glaciers in a region, it becomes necessary to select one or more as representative of the glaciers in that region. The results obtained from an intensive mass-balance study on carefully selected representative glaciers can then be extrapolated over the entire glacierized region.

Østrem and Stanley (1966) listed certain criteria upon which the selection of glaciers for mass-balance studies made during the International Hydrological Decade was based. The primary purpose of their glaciological investigations was to determine the mass balance of the glaciers. Although the mass-balance study was only one aspect of the overall program on Casement Glacier, the considerations they applied for the selection of glaciers for their investigations are applicable to wider studies also. They are as follows (Østrem and Stanley, 1966):

a. The glacier must have a well-defined catchment area and the degree of glacierization must be as high as possible so that the meltwater stream depicts conditions on the glacier rather than conditions on the surrounding terrain.

b. The size of the glacier should be comparable with all glaciers in the area of study but small enough to be fully examined by a 2-3 man party. (The upper limit of such an area is probably 10-15 km^2). In special cases, when great economic interests are involved, it might be possible to have more people involved in the field measurements and thus a larger glacier area could be examined.

c. The range in altitude between the glacier tongue and the upper firn area should be as large as possible, or at least cover the main part of the range for the glaciers in the area under study.

d. The glacier should be drained by a single meltwater stream with local conditions favorable for discharge measurements close to the glacier snout.

e. The glacier should have relatively easy access so that it will be feasible to visit it throughout the year without the extensive use of helicopters, etc. Easy access should, however, not be overemphasized; an ideal glacier should not be omitted and replaced by another less suitable for reason of accessibility alone. This question must be decided for each particular glacier depending on available resources.

f. The glacier should have few crevasses as they make the work unnecessarily risky for observers and may restrict proper observations to only a small area. However, if a representative glacier has a great number of crevasses the value of this point must also be considered in each particular case.

g. The glacier should be situated in an area for which reliable maps and good air photographs are available or can be readily obtainable shortly after investigations have started. All accumulation and ablation measurements must be plotted on maps, and the scale of 1:10,000 is generally most suitable for this purpose. A contour interval of 10 meters will be appropriate for the glacier surface, 50 meters will be sufficient for the surrounding area. The map must cover the entire catchment area above the site of the river observations.

Points "e" and "g" do not apply to the Casement Glacier study, and on four other points Casement Glacier does not meet Østrem and Stanley's requirements: (a) it does not have a well-defined catchment basin, being formed by the merging of at least seven smaller tributaries, several of which share a common catchment area; (b) although it is comparable in size with the other main glaciers in the area, such as Muir, Riggs, and McBride Glaciers, it is more than ten times the maximum recommended size; (d) the glacier is not drained by a single meltwater stream, so the measurement of the mass balance in terms of the discharge was not possible, and (f) the glacier's surface is disrupted by three major icefalls and numerous minor ones, rendering travel on the glacier difficult and hazardous. Recommendation (c) is the best satisfied, as the range in altitude from the terminus to the top of the firn basins is about 2,000 m.

However, despite these disadvantages, Casement Glacier was chosen for the investigation because the glacial history of the region is well known and because of the excellent logistical support available from the U. S. National Park Service.

Classification of the Glacier Type

According to Ahlmann's morphological classification scheme for glaciers (Ahlmann, 1948, p. 61), Casement Glacier is a dendritic valley glacier, as it is confined to a definite path and occupies a valley system. Casement Glacier is temperate according to another of Ahlmann's classifications, because the ice is at the pressure-melting temperature, except during the winter when the top few meters are colder.

Climate

The climate of Muir Inlet is cold maritime, as is all of coastal southeast Alaska. It is characterized by small diurnal and seasonal temperature variations, high humidities, frequent fog, considerable cloud cover, and high precipitation. However, some of the adjacent mountainous region may be classified as having a cold snow forest climate with cool summers.

Geology

The bedrock geology of the Glacier Bay region has not been examined thoroughly. The most extensive work was done in 1966 by U. S. Geological Survey geologists who, with helicopter support, made a thorough reconnaissance of the bedrock geology of Glacier Bay National Monument. Their results have not been published; however, a personal communication with preliminary results from the party leader, David A. Brew, provided more complete knowledge of the geology around the Casement Glacier.

The Glacier Bay region is a small portion of the Alaska Coast Ranges, which, in turn, are a part of an extensive structural province that extends from the Aleutian Islands down through the Andes of South America. According to Miller and others (1959), the basic structural unit in the Glacier Bay region is the Prince of Wales geanticline which is cut longitudinally by northward extensions of the Denali fault system. Most of the major glaciated and glacierized valleys and fjords lie parallel to these old folds and faults which provided a more easily eroded bedrock.

Most of the rocks in the Glacier Bay region are limestones, argillites, and metasediments, ranging in age from Late Silurian to Middle Devonian. In some localities these rocks have been extensively folded, faulted, and intruded by numerous diabase dikes and sills. These structures are frequently well exposed on the steep, glacially smoothed walls of the fjords, such as Muir Inlet.

Four rock types make up most of the bedrock in the vicinity of Casement Glacier: granitic rocks, hornfelsed detrital clastics with some unmetamorphosed volcanics, detrital clastics, and carbonates. Locally, porphyritic phases of granitic intrusions have resulted in intense alteration of the adjacent rocks. There are two types of volcanic units adjacent to Casement Glacier. A body of greenstone which has developed from a volcanic breccia is exposed in Forest Creek, and a reddish-weathering unit of volcanic breccia, which may be related to the occurrence in Forest Creek, occurs on the north side of Red Mountain.

Field Logistics

Logistic support each field season was provided by the U. S. National Park Service. Their support included transportation of men, equipment, and supplies from Juneau to Muir Inlet and back aboard the MV Nunatak, resupply and mail trips to Muir Inlet, and daily radio communication with Park Service headquarters at Bartlett Cove. From the shores of Muir Inlet, the men and equipment were moved to and from the campsites each season using a chartered helicopter from Juneau.

In 1965 the main camp was established on the true right side of the glacier 5 km from the terminus (Fig. 3). During the 1965 season most of the work was done on the lower portion of the glacier. In 1966 the main camp was moved 14.5 km upglacier to a point that afforded ready access to most of the upper portion of the glacier (Fig. 3). A tent was also set up at the 1965 campsite to provide a base of operations for work on that section of the glacier. A third camp was established in 1966 at the site of the tunnel study. The camp organization in 1967 was the same as in 1966.

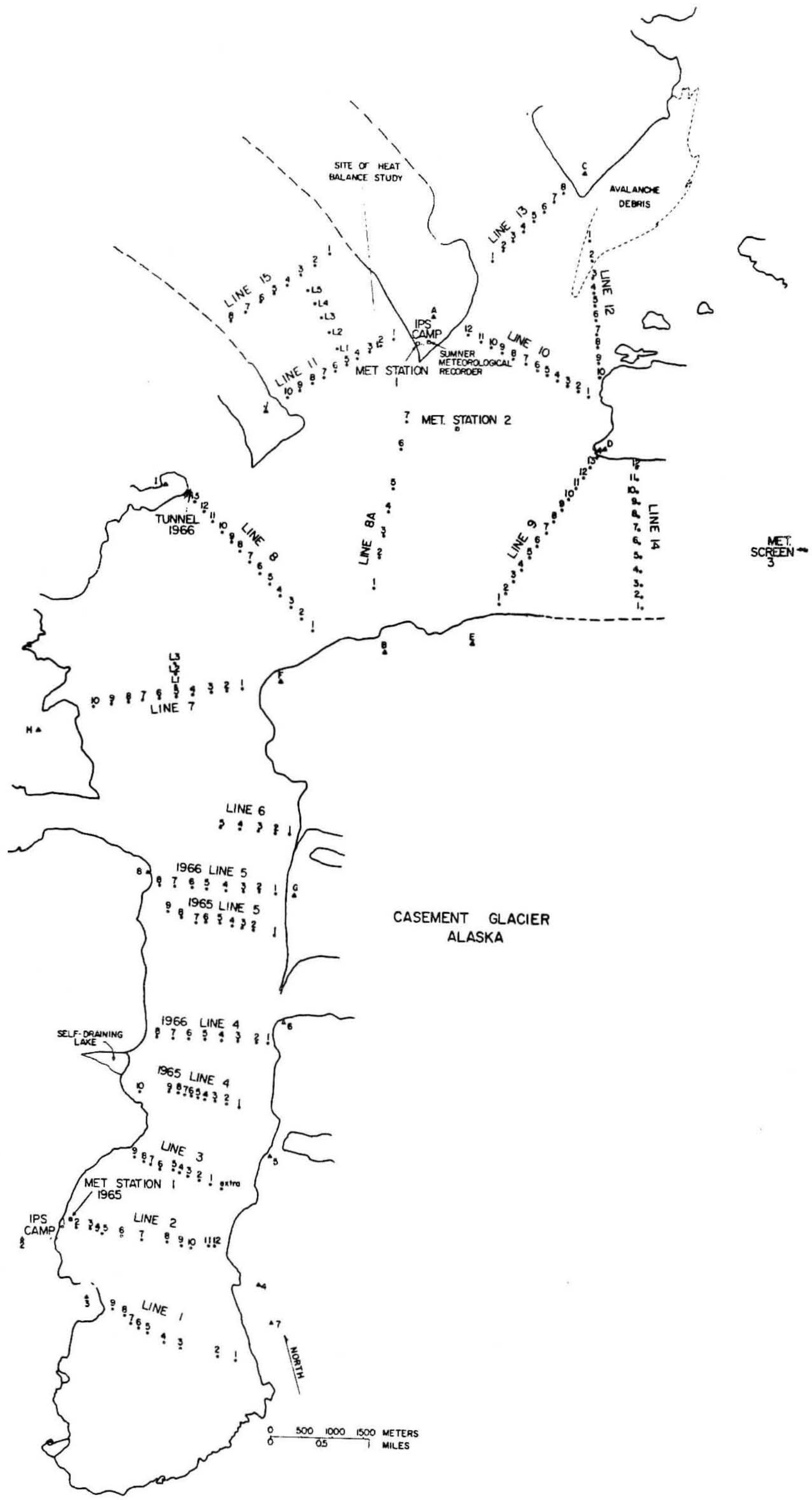


Fig. 3 - Map of Casement Glacier showing the locations of the camps, meteorological stations, survey stations, rows of movement stakes, and ice tunnel.

CHAPTER II

ICE MOTION STUDIES

The major objective of the survey program was to establish and maintain a triangulation network in order to determine the distribution of surface velocities over representative portions of Casement Glacier and its tributaries. These velocity determinations would then be used in the assessment of the mass budget of the glacier. To achieve these objectives, fixed triangulation stations were established on the mountain sides from which markers drilled into the ice could be surveyed by intersection.

A secondary objective of the ice motion studies was to determine the trajectory of a particle through the glacier. Originally, it was intended that this should be done by measuring the variation of the inclination of holes drilled through the glacier to determine the variation of velocity with depth, and to combine this with accumulation and ablation rates to arrive at the desired trajectory. Because the deep drilling program was not successful, these calculations had to be made by using the englacial velocities calculated from a theoretical formula derived by Nye (1952) and the vertical component of the ice velocities (see Chapter VI, Englacial Velocity Profiles).

Instrumentation

Kern DKM-2 theodolites, which can be read directly to one second of arc, were used for all of the surveying. During the first two summers, only one instrument was used. However, on many days in the first two seasons bad weather made surveying impossible and, to make sure the survey was completed, two instruments were used in 1967.

Triangulation

Baseline Measurement

In order to calculate the coordinates of the fixed stations and, from them, the positions of the surface velocity markers, a 1195.050 m baseline was laid out on a flat snow surface by the flat-chaining method, using a 100 m chrome-clad steel tape under 15 pounds tension. The location of the baseline is shown in Figure 4. The measurement was done twice, the difference being 0.015 m. The standard corrections for temperature and slope have been made to the measured line. The given length is probably accurate to 0.010 m.

To establish a local grid system, the southern end of the baseline was given the coordinate values 10,000.000 and 10,000.000 and the

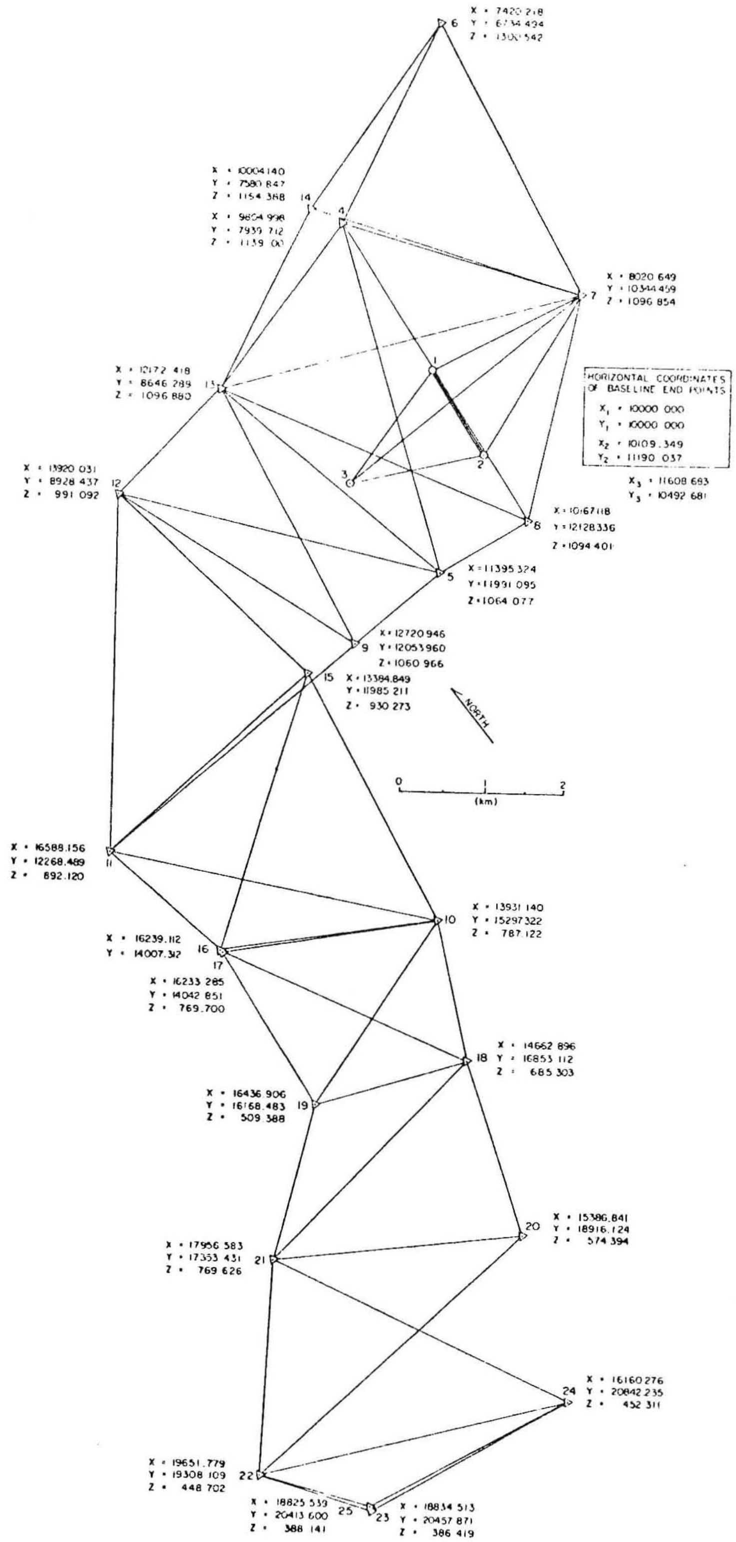


Fig. 4 - Diagram of the triangulation network for Casement Glacier.

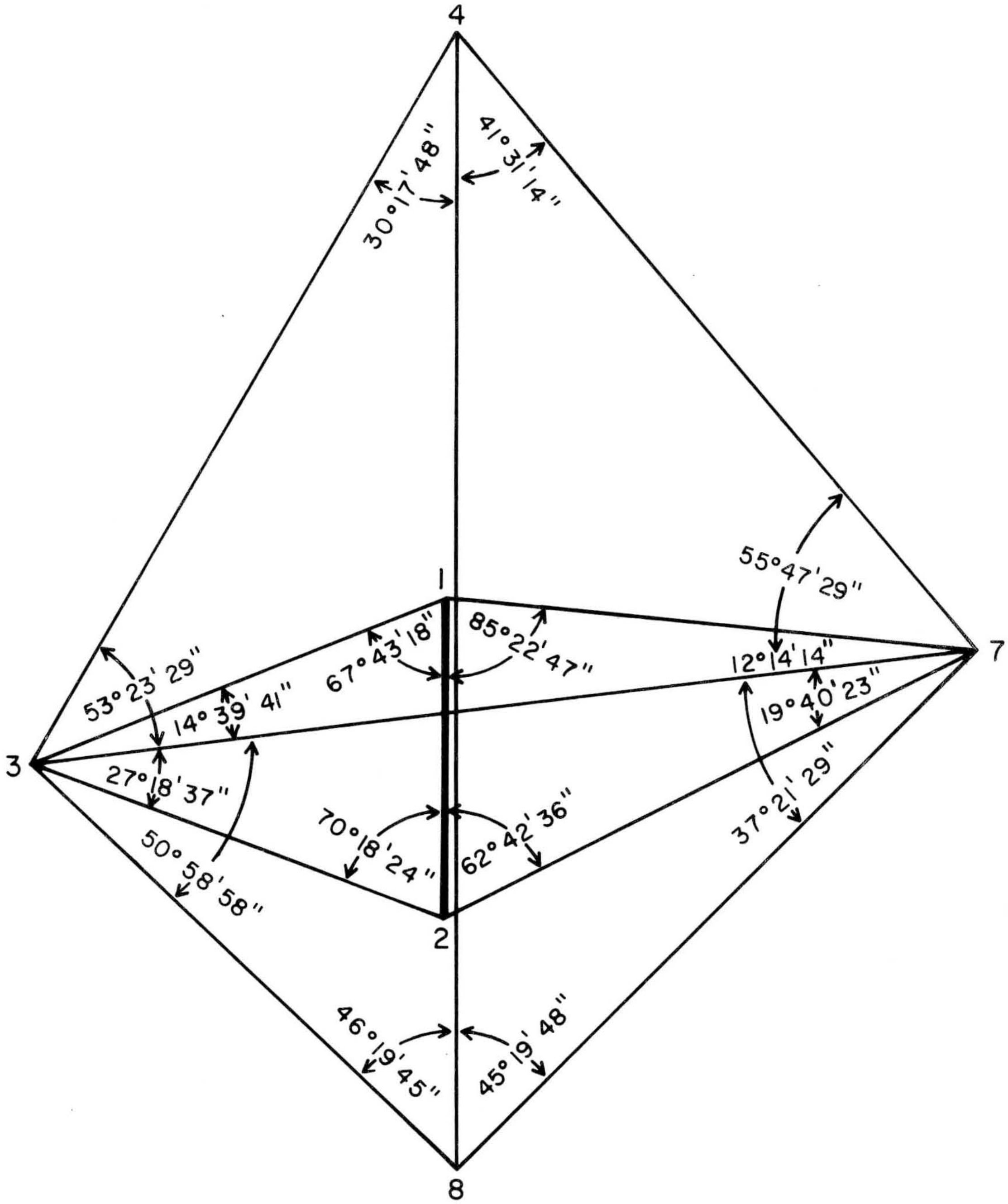


Fig. 5 - Diagram showing the layout of the measured baseline (1-2) and the first two quadrilaterals in the extension of the baseline.

positions of all the cairns and markers were calculated relative to these coordinates. The azimuth of the baseline was estimated from the U.S.G.S. map (Skagway A-3 sheet) to be 5°15'. This value is probably accurate to ±2°.

Fixed Stations of the Triangulation Network

An extensive triangulation network was established during the three seasons. Most of the stations were occupied during the velocity surveys. The remaining stations were set up so that the entire network could be tied together. The coordinates in the local grid network were calculated by triangulation using the measured baseline as the first side.

Stations 17 through 27, excluding 19, (see map, Fig. 4) were established in 1965. Stations 1 through 12 were set up in 1966 and 1967. A temporary cairn, 19, was set up on the ice between cairns 21 and 27 to allow extension of the triangulation network past a steep portion of the valley wall.

Triangulation Network Scheme

The triangulation network (Fig. 4) consisted of eight braced quadrilaterals and nine triangles. They are, in order, from the baseline to the terminus:

1. Quadrilateral 1-3-2-4
2. Quadrilateral 4-7-8-3
3. Triangle 4-6-7
4. Quadrilateral 4-7-8-13
5. Triangle 7-13-14
6. Quadrilateral 4-7-5-13
7. Quadrilateral 13-5-9-12
8. Triangle 9-11-12
9. Triangle 15-11-12
10. Quadrilateral 15-10-16-11
11. Triangle 16-10-17
12. Quadrilateral 17-10-18-19
13. Triangle 18-21-19
14. Quadrilateral 21-18-20-22
15. Triangle 21-22-24
16. Triangle 22-24-23
17. Triangle 22-24-25

Extension of the Baseline

Measurement of Angles

Stations 1 and 2 were set up on the snow at the two ends of the measured baseline (Fig. 5). Station 3 was erected on the snow about 1.6 km west of the midpoint of the baseline. From points 1 and 2, cairns 3, 4, 7, and 8 were surveyed. Then, each of the other stations, 3, 4, 7, and 8, was occupied and all the other stations in the baseline extension were surveyed. This work produced two quadrilaterals with the measured baseline as the diagonal of the smaller figure.

From each of the remaining cairns on bedrock, and the temporary one on the ice, 19, the horizontal and vertical angles to all the other visible cairns were observed. Generally, the angles were taken as the means of two sets of measurements (one set of angles consists of both forward and reverse pointings), but frequently, more than two sets of angles were used in the computations. The maximum acceptable error for closure of a round of horizontal angles was five seconds. The averaged angles from the two pointings were added and the departure from 360° (usually less than ten seconds) was distributed equally among all the angles. The mean vertical angles from the two sets of measurements were averaged, the difference usually being less than five seconds.

Adjustment of the Figures

The misclosures for the triangles in the network were adjusted by adding or subtracting one-third of the misclosure to each angle. The errors were so small (from one to twenty-two seconds) that weighting of the error distribution was not necessary.

The adjustment of the errors of misclosure in the quadrilaterals was done by electronic computer, using a program by Marangunić (1970). The program adjusts the angles by the angle-and-side method of Wright and Hayford (in Breed and others, 1962) so that the sum of the interior angles is 360°. The unadjusted and adjusted angles for each of the figures in the network are given in Appendix A.

Strongest Route for the Extension of the Baseline

After the triangles and quadrilaterals were adjusted, the strongest route through the adjusted network for the extension of the baseline was calculated, according to the U. S. Coast and Geodetic Survey method (Reynolds, 1928). This method tests the strength of various routes through a network by computing the probable error of a triangle side. The strongest route is given in Figure 6.

Calculation of X, Y, and Z Coordinates of the Survey Stations

The coordinates of the south end of the baseline were arbitrarily set at 10,000.000 and 10,000.000. The length of the baseline was

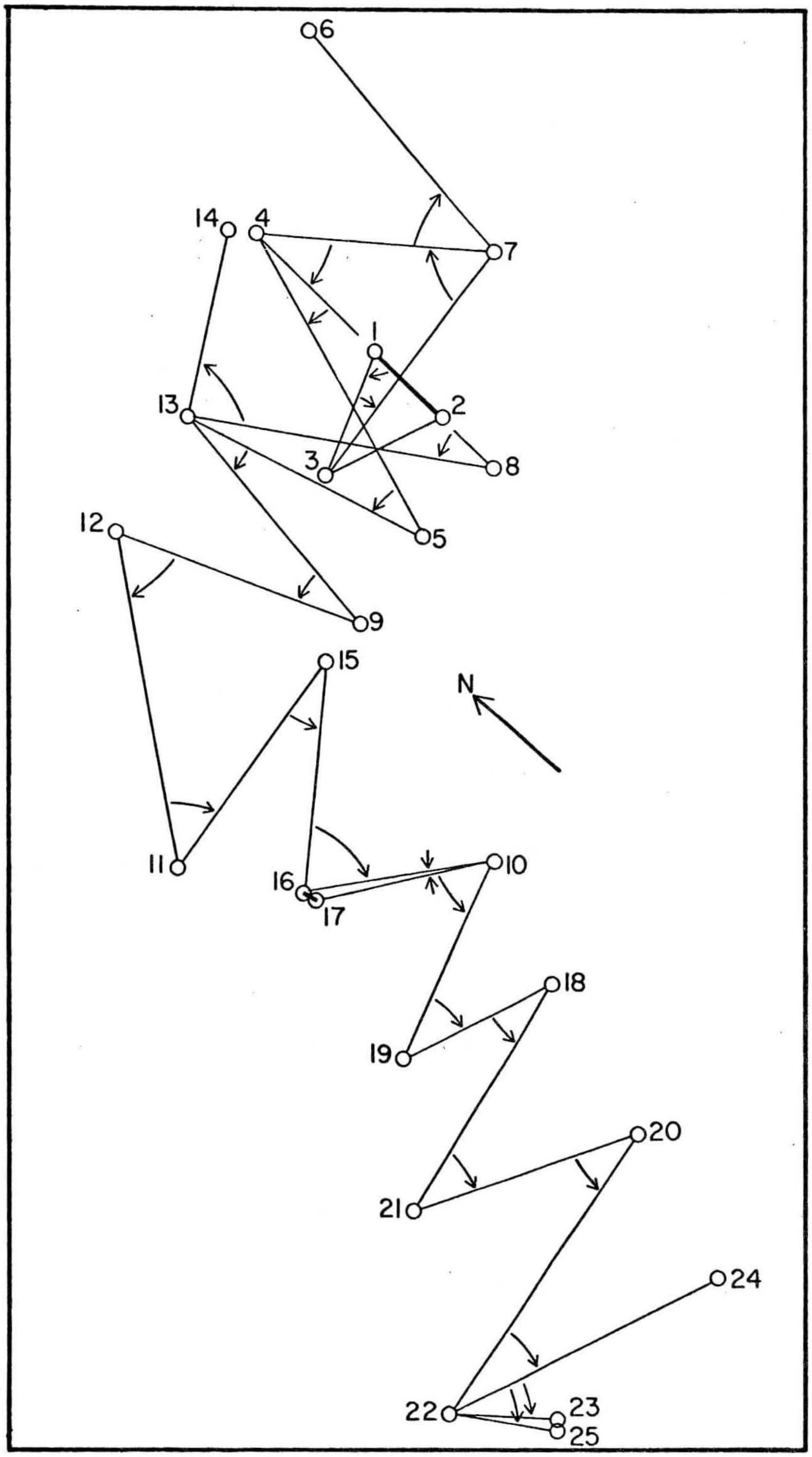


Fig. 6 - Diagram showing the strongest route through the triangulation network for the calculation of the coordinates of the cairns.

1,195.050 m and its azimuth estimated to be 5°15'. From this, the coordinates of the north end can be calculated:

$$X_2 = X_1 + 1195.050 \ (\sin 5°15')$$

$$Y_2 = Y_1 + 1195.050 \ (\cos 55°15')$$

The coordinates of the remaining stations were calculated in the following manner (using Fig. 7):

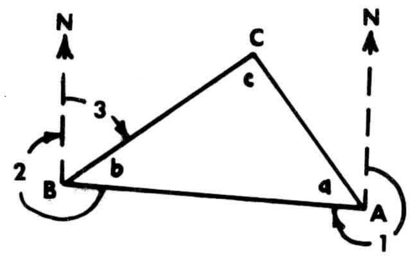


Fig. 7 - Diagram showing how the coordinates of the cairns were calculated.

$\measuredangle 1$ is the azimuth of the known line between points A and B

$\measuredangle 2$ is the measured angle from BA to BC $(360° - \measuredangle b)$

$\measuredangle 3$ is the azimuth of the new direction BC $(= \measuredangle 1 \pm 180° + \measuredangle 2)$

1. The distance, D, between any two stations, A and B, whose coordinates are known may be calculated from:

$$D = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}$$

2. The azimuth of the new forward line to the next triangulation station BC is obtained by adding the observed angle from the reference station at the opposite end of the known line to the azimuth of the known line AB.

3. The distance BC is computed by the sine law:

$$BC = \frac{BA \sin \measuredangle a}{\sin \measuredangle c}$$

4. The coordinates of station C are then found by:

$$X_C = X_B + BC \sin \measuredangle 3$$

$$Y_C = Y_B + BC \cos \measuredangle 3$$

In order to calculate the Z coordinate for each station, it is necessary to know the elevation of one of the cairns. For the Casement Glacier Survey, the elevation of cairn 4 was determined by helicopter altimeter on five round trips to and from sea level during the move-in for the 1967 season. This value (1,145 m) was used in the first calculations of the elevations of the triangulation stations. From two of the stations, 17 and 24, rays to the summit of Mt. Wright were observed in 1965. Substituting the observed angles into the survey program, horizontal coordinates and the "height" of Mt. Wright were calculated. The calculated height was compared with the known height and the difference was attributed to an error in the original elevation of cairn 4. The height of cairn 4 was adjusted by the difference (6 m) and new Z coordinates were calculated for all the survey stations. Using the adjusted value, the two values calculated for the height of Mt. Wright from the individual rays are 1,565.74 m and 1,566.99 m (mean value 1,566.37 m).

Surface Velocity Measurements

Aluminum tubes 1.87 cm in diameter and 366 cm long were used as survey-ablation markers. Brightly colored flags were tied near the tops of the poles to make them easier to see.

Positions and horizontal velocities were determined for 180 stakes, the locations of which are shown in Figure 9. The only stakes for which survey data are available for all three seasons are those in lines 2 and 8a. In 1965 seven transverse rows of stakes were placed in the ice, but only six were surveyed twice that summer. Line 8a was not installed until 24 August and was, consequently, only surveyed once. In 1966 nine new lines of movement stakes were placed in the ice; most of them were positioned around the new camp farther upglacier. Lines 1, 3, 4, 5, and 6 were not surveyed after the first season, and new lines were added to replace lines 4 and 5. In 1967 two more lines, 14 and 15, were added to those already existing.

The positions of each stake were determined by intersection from two of the triangulation stations. One set of horizontal angles was shot from each triangulation station to the lowest visible part of the stake. The vertical angles were shot to the top of the stakes because the surface was constantly lowering and a fixed reference point was required in order to calculate the vertical velocity.

Calculation of the Coordinates of the Survey Markers

The positions of the velocity markers were calculated by first using the Law of Sines, the measured angles from the two cairns to each of the markers, and the known distance between the cairns, to compute the side lengths of the triangles (Fig. 8, triangle A-C-8). From cairns A and C, the horizontal angles, a and c, to the marker, 8, are measured. Side length, L, is known from the triangulation. Side lengths a_8 and c_8 can be calculated from these equations:

$$a_8 = L \frac{\sin c}{\sin(a+c)} \qquad c_8 = L \frac{\sin a}{\sin(a+c)}$$

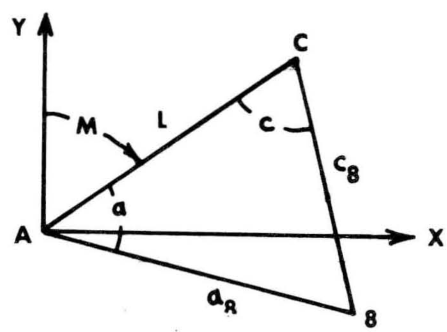


Fig. 8 - Diagram showing the method of calculating the coordinates of the velocity markers by intersection from the cairns.

After the side lengths have been computed, the X and Y coordinates of the marker can be calculated from the following equations:

$$X_8 = X_A + a_8 \sin(a+M)$$

$$Y_8 = Y_A + a_8 \cos(a+M)$$

where M is the angle between the known side and the grid north (Y axis).

The differences in elevation between the two survey stations and the tops of the markers were calculated by the following equations:

$$\Delta Z_C = Z_C - Z_B = a \tan C - HI_C - R_C$$

$$\Delta Z_A = Z_A - Z_B = c \tan A - HI_A - R_A$$

where HI is the height of the instrument and R is the combined correction for refraction and the Earth's curvature. The elevation for any survey marker was taken as the arithmetic mean of the two computed elevations. This difference was almost always less than 0.5 meter.

Computation of the Surface Velocities

From the positions of the markers in successive surveys, the magnitude and azimuth of the surface velocity was calculated, again using Marangunić's (1970) computer program. The vertical velocities of the surface markers were calculated from a combination of the successive surface elevations, as computed from the survey data, and the ablation data for each stake.

Accuracy of the Velocity Data

The most important question which must be asked about the surface velocity measurements is how accurate are the calculated velocities as indicators of the surface velocity. The precision of measurement is determined by a large number of factors, some of which are: accuracy of the instrument setup, pointing and reading of the instrument, atmospheric refraction, stability of the target, resetting the instrument for remeasurement, and the human error in reading the instrument.

Location of Fixed Points

The error in the length of an extended side in a triangulation network can be determined from the error in the side length from which the new length was calculated and the angular errors in the triangulation. Clark (1951) gives an equation for computing the standard error, m_a, in the exit side of triangle ABC (Fig. 7) with the error in side AB, m_b, and the standard error of the adjusted angles, m_α:

$$m_a^2 = \left(m_b \frac{a}{b}\right)^2 + \frac{2}{3} a^2 \frac{m_\alpha^2}{\rho^2} (\cot^2 A + \cot^2 B + \cot A \times \cot B)$$

where ρ is the conversion factor for radians into seconds, 206264.8. This equation reduces to:

$$m_a = m_{BC} = \pm BC \sqrt{\left(\frac{m_{AB}}{AB}\right)^2 + \frac{2}{3}\left(\frac{m_\alpha}{\rho}\right)^2 (\cot^2 A + \cot^2 B + \cot A \times \cot B)}$$

Starting with an initial error in the baseline of ± 0.010 m and taking the standard error for the measurement of the horizontal angles as five seconds, the error in the computed length of each extended side in the entire survey network was calculated following the calculated strongest route through the network. The magnitude of the error increases as each successive length is computed from the preceding side. The computed errors in the side lengths are small and do not affect the calculation of the coordinates of the motion markers.

Motion Markers

Errors in the velocity at a motion stake result from errors in the calculated positions of the marker and the error due to time lapse between the surveying of the two rays to the marker.

The error in position depends upon the errors in the measurement of the angles, the error in the length of the baseline, and the position of the markers relative to the baseline. Redundant observations were not made in the positioning of the stakes by intersection. An estimate of the position errors can be made assuming that all markers were surveyed with the same precision. Brecher (1966) determined a standard error of intersection of ± 8 seconds by setting up at 11 markers in addition to the fixed stations, thus observing all of the angles in the triangles. The computed errors in the sides used for the motion surveys are small and can be neglected. The errors in the position of each marker, parallel and perpendicular to flow, resulting from these factors have been computed. The results are given in Table 1.

TABLE 1

ERRORS IN THE COORDINATES OF THE MOTION MARKERS

Marker No.	Error in Coordinates X(m)	Error in Coordinates Y(m)	Marker No.	Error in Coordinates X(m)	Error in Coordinates Y(m)
1-3	.002	.003	7-1	.025	.090
1-8	.239	.216	7-10	.004	.100
2-1	.013	.012	8-1	.006	.044
2-10	.133	.063	8-13	.034	.001
3-1	.002	.040	9-1	.021	.075
3-5	.001	.006	9-13	.011	.013
3-7	.007	.063	10-3	.002	.040
3-9	.006	.061	10-11	.018	.062
4-2	.006	.032	11-1	.094	.013
4-9	.010	.031	11-10	.067	.016
5-1	.014	.025	12-3	.016	.023
5-9	.022	.128	12-10	.000	.010
6-2	.032	.008	13-1	.205	.077
6-5	.064	.018	13-4	.002	.001
2-1	.009	.027	13-4	.045	.011
2-9	.389	.034	13-8	.073	.045
4-1	.154	.071	14-4	.019	.023
4-8	.143	.075	14-11	.056	.025
5-1	.015	.057	15-1	.016	.024
5-7	.055	.043	15-7	.007	.014

The surveying of each row of stakes from the two fixed stations was almost always done on the same day. This was particularly true during the last summer, 1967, when simultaneous observations were often made. Consequently, although some time may have elapsed between the two observations of a surface velocity marker, it was almost always just a few hours, in which time the target might have moved a maximum of 5-10 cm downglacier. Therefore, no attempt was made to adjust the data for movement between the two sets of observations. The time of the observations was recorded as days and decimal fractions of days; the mean of the two times was used for the velocity calculations.

The vertical coordinate of the stakes was less accurately determined because of atmospheric refraction. However, the mean difference between the two calculated elevations for each marker in all of the surveys was only 0.4 m. The mean error is one-half of this value.

Results of the Ice Motion Studies

Time Variation of Velocity

Many workers have noted time-variations in surface velocity, with higher velocities being observed during the summer in the ablation zone and, often, higher velocities during the winter in the accumulation zone. As most of the velocity markers on Casement Glacier were surveyed twice each summer, the summer velocities could be determined for comparison with the mean annual velocity and the "winter" velocity, which is taken as the velocity for the other months (usually from the end of August one year to the beginning of July the succeeding year). Horizontal surface velocity vectors are shown for Casement Glacier in Figure 9.

Meier (1965) states, "The coupling of a glacier to its bed is a most important current problem in glacier flow studies." It has been suggested by a number of investigators (Paterson, 1961, 1964; Meier, 1960; Battle, 1951; Elliston, 1963; Friese-Greene and Pert, 1965) that observed daily and seasonal variations in surface velocity are, in large part, the result of changes in the basal sliding rate. To date, the only direct substantiation of this suggestion has been from observations of variations of slip rate in a glacier cave in Østerdalseisen, Norway (Theakstone, 1967).

A summary of the seasonal velocity data from the upper portion of Casement Glacier is presented in Table 2. In general, the summer velocities are measurably greater than the mean annual or winter velocities. These results, combined with the results from the ice tunnel investigations (in 1966 and 1967 measurements were made on the rate of basal sliding in a tunnel in the glacier; see Fig. 3 for tunnel location), aid in the understanding of the causes of the observed seasonal changes in surface velocity.

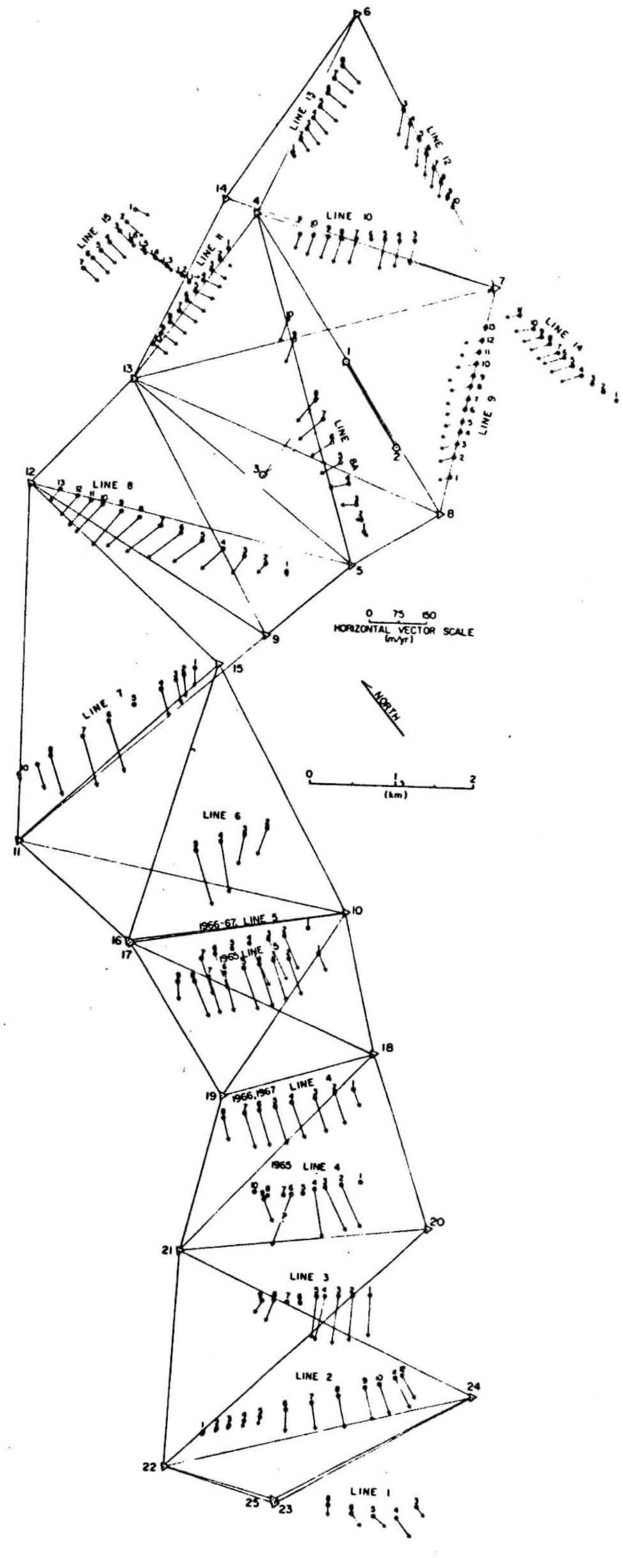


Fig. 9 - Diagram showing the horizontal surface velocity distribution over Casement Glacier. The vectors denote ice speed and direction.

TABLE 2

PARTIAL LISTING OF SEASONAL VELOCITIES FROM THE UPPER REGION OF THE GLACIER

Marker No.	1966 Summer Vel. (m/yr)	1966-1967 Winter Vel. (m/yr)	1967 Summer Vel. (m/yr)
9-4	60.89	56.82	56.29
9-5	64.50	58.19	62.06
9-6	65.17	59.90	61.09
9-7	65.87	60.68	63.24
9-8	66.19	60.80	63.09
9-9	74.65	60.18	-----
9-10	66.30	58.13	65.03
9-11	64.48	54.83	58.66
9-12	61.50	49.06	52.51
10-4	97.55	89.53	87.25
10-5	99.37	91.81	88.48
10-7	95.15	86.81	89.19
10-8	90.27	81.20	84.60
10-9	83.65	75.26	79.97
10-10	74.17	64.85	69.05
11-2	41.45	33.40	37.64
11-3	60.77	50.62	53.56
11-4	75.76	59.95	61.19
11-5	71.53	62.04	67.12
11-6	70.58	63.89	68.08
11-7	75.09	64.00	66.61
11-8	69.63	62.35	65.20

The tunnel observations will be discussed in detail in Chapter VII of this report. Let it suffice to say at this point that the observed decrease in surface velocity during the winter (a decrease of 14 per cent was observed at stake 8-13 only about 100 m from the entrance of the tunnel) may be compared with the 20 per cent decrease in the basal slip rate in the tunnel.

The difference between the extreme summer and winter velocities was probably considerably greater than the observed 14-20 per cent. The "winter" rates include the time from the final survey on 15 August 1966 to the initial survey on 8 July 1967. This includes at least two months of moderate ablation when there was abundant meltwater available for basal lubrication, so that the velocity averaged over the whole period is probably anomalously high as an indicator of the true winter velocity.

At almost all of the survey markers, the velocity for the 1967 summer was significantly lower than for the 1966 summer. A similar decrease was observed in the tunnel measurements; the mean basal slip rate decreased from 2.9 cm/day in 1966 to 2.6 cm/day in 1967.

The observed decrease in surface velocity from 1966 to 1967 could have resulted from three causes: (1) decreased thickness due to ablation, (2) change in surface slope, or (3) a change in the quantity of lubricating water at the base of the glacier. The mass of a column in the upper section of the glacier decreased from 1966 to 1967 by approximately 120 g/cm^2 of water (ρh). This represents a loss of from 0.3 to 2.4 per cent of the mass of a column of ice. Because the velocity is proportional to the one-fourth power of the thickness, the estimated decrease in thickness could not be capable of producing the observed decrease in velocity. A change in the surface slope could produce changes in the velocity, but no changes in the surface slope were observed.

Thus, this observed decrease in velocity was almost certainly the result of less lubricating water at the base of the glacier in 1967 than in 1966. The water is derived from two sources: precipitation and ablation. Precipitation records show that during the intervals from the initial to the final surveys each season, there was 18.6 g/cm^2 of rainfall in 1966 and 24.8 g/cm^2 in 1967. This difference alone would have produced results opposite to those observed. However, ablation records reveal that, because of an extended period of fair weather in July, 1966, the ablation in that year between the initial and final surveys exceeded that in 1967 by 10-15 g/cm^2. As a result, the total water (from precipitation + ablation) available for basal lubrication was greater in 1966 and, consequently, the slip rate was higher (as observed) and the surface velocities likewise were higher in 1966 than in 1967.

Absolute Vertical Component of Velocity

The vertical component of velocity, V_z, is a measure of the absolute rate of change of elevation of a layer of ice; it was determined along a longitudinal line relative to a fixed coordinate system. The value of V_z was calculated from the following equation:

$$V_z = (\triangle E - A - V_d)/\text{unit time}$$

where $\triangle E$ is the difference in elevation of the surface at the times of the two surveys, A is the surface lowering due to ablation, and V_d is the change in elevation resulting from a surface velocity, V_s, moving down a slope $\alpha (V_d = V_s \times t \times \tan \alpha)$.

For a typical valley glacier in equilibrium state, the value of V_z is positive in the ablation zone and negative in the accumulation zone with a cross-over at the position of the steady-state equilibrium line. The magnitude of V_z is small at the terminus and at the head of a glacier.

For Casement Glacier the equilibrium line for steady-state condition is near line 8. Above this line the values of V_z decrease to a minimum of -6.2 m/yr at marker 9-7 and -6.1 m/yr at stake 12-3. Downglacier from line 8 the values of V_z are less typical. At stake 7-5 the value was -13.1 m/yr. This is in a region where the values should be positive. The reason for this high value may be that at this point the glacier is thinning rapidly as it flows over a second icefall (immediately below line 7) and the calculated value of V_d may not be large enough. In the region of the glacier between the first and second icefalls, the values of V_z are still negative. The values were calculated several times for stakes in lines 4 and 5 and appear to be real. No explanation has been suggested to account for this anomalous behavior. The values of V_z along lines 1, 2, and 3 are positive and reflect the upward mass flux. The values of V_z along the centerline of flow are given in Table 3 and are presented graphically with the englacial velocities along the centerline (see Figure 23, Chapter VI).

TABLE 3

VERTICAL VELOCITIES ALONG CENTERLINE

Stake No.	Vertical Vel. (m/yr)	Stake No.	Vertical Vel. (m/yr)
1-4	+16.0	7-5	-13.0
2-9	+4.4	8-7	-1.7
3-4	+5.4	9-7	-6.2
4-5	-2.8	14-5	-3.1
5-4	-1.3		

CHAPTER III

ICE THICKNESS DETERMINATIONS

Introduction

In order to estimate the thickness of the ice and the configuration of the glacier's bed for englacial velocity and mass discharge calculations, measurements were made in 1965 and 1966 of the changes in gravitational acceleration along ten of the transverse rows of survey markers discussed in the previous chapter.

Principles

The gravimeter was first used to measure the thickness of glacier ice by Martin in Greenland in 1948. The method is based on the fact that ice has a lower density than the bedrock surrounding the glacier. Thus, by measuring changes in gravitational acceleration across the surface of a glacier, one can calculate the thickness of a slab of ice required to produce the calculated Bouguer anomaly after all of the necessary corrections have been made to the observed gravity values.

Field Procedure

The gravity measurements in 1965 were made using a Worden Master Geodetic model gravimeter (instrument 602) belonging to the Department of Geology, The Ohio State University. The gravimeter used in 1966 was a LaCoste-Romberg instrument (number 41) on loan from the U. S. Army Map Service, Washington, D.C.

In both 1965 and 1966 base gravity stations were established at the respective base camps from which the surveys along the rows of movement stakes were conducted. For the gravity survey of each transverse row of stakes, a bedrock station was occupied at each end. In 1965 the base station was reoccupied after the completion of each row of stakes to check the instrumental drift. Drift correction did not exceed 0.2 mgal/hr and was distributed linearly with respect to the time of observation. The LaCoste-Romberg instrument has a very low drift rate and so frequent returns to the base station were not necessary in 1966. Most of the gravity data from the 1965 season were collected by Dr. C. Bull. The writer was responsible for the field measurements in 1966 and for the reduction of all the data.

Gravity Stations

Four gravity traverses at the lower end of the glacier were made in early July 1965. The remaining six traverses were made in July 1966. A total of 122 stations were occupied, 18 of which were on bedrock. The elevations and positions of all the stations on the glacier and some of the bedrock stations were determined by intersection from stations in the triangulation network. The elevations of the remaining stations on bedrock at the ends of the traverses were determined by altimetry and their positions estimated from the field data. The elevations of the glacier stations relative to each other are probably accurate to ± 0.2 m, and the elevations of the bedrock stations are known to the nearest meter relative to the ice stations. For the latitude corrections, the relative horizontal positions of the stations in the local grid system are probably accurate to the nearest 0.5 m.

Reduction of the Data

Bedrock and Ice Densities

The density of the glacier ice was measured in the field to be 0.9 g/cm^3 which agrees with the traditionally accepted value (Seligman, 1950). The mean of the densities of 15 unweathered samples from the surrounding bedrock measured with a Jolly balance was 2.79 g/cm^3, the range being from 2.66 to 3.03 g/cm^3 (Table 4). These rocks are considered to be a representative sample of the bedrock geology adjacent to the glacier.

Table 4

ROCK DENSITY DETERMINATION
FOR GRAVITY DATA REDUCTION

Rock type	Number of samples	Range of densities	Mean density
Granite	3	2.77-2.82	2.80
Syenite	4	2.66-3.03	2.83
Hornfels	2	2.66-2.83	2.75
Schist	1	2.88-2.89	2.88
Marble	5	2.68-2.72	2.72
	15	2.66-3.03	2.79

Combined Free-Air and Bouguer Corrections

A Bouguer correction was calculated for each station, using the elevations that were derived from survey data and altimetry done with the gravity surveys and a correction factor of 0.1919 mgal/m. This factor was calculated from the following equation:

$$\Delta g = 0.3086h - 0.04185\rho h$$

where Δg is the combined Free Air and Bouguer correction, h is the difference in elevation in meters between the station and one of the bedrock stations, and ρ is the density, taken as 2.79 g/cm^3.

Latitude Correction

A latitude correction factor of 7.17×10^{-4} mgal/m was calculated from the equation (Dobrin, 1960):

$$g_1 = 1.307 \times \sin \varphi \text{ mgal/mile}$$

where φ is the latitude of the station (taken as 59° for all stations). The correction for each station in a given transverse line was computed using differences between the Y coordinate value of the station as determined from the survey program and the bedrock station. The correction is negative for stations north of the base and positive for stations south of the base.

Terrain Corrections

The gravitational effect of the surrounding topography was calculated using the Hammer method (1939). The terrain corrections were made from zone D to zone J (radius of 6,653.84 m) using topographic maps constructed by the U. S. Geological Survey from 1948 aerial photographs (sheets Juneau D-6, Skagway A-3, and Mt. Fairweather D-1). The surface elevations in the upper portion of the glacier agree fairly well with the 1948 contour lines. Where they do not agree, new contours were drawn using elevations determined in the velocity survey. A density of 2.79 g/cm^3 was used for the corrections in all compartments. The maximum terrain correction was at the bedrock station at the east end of line 1 where the value was 6.35 mgals. The error on the glacier due to local compartments is small because of the low surface relief.

Regional Gradients

There are no data on the regional gravity gradient to permit a proper correction of the observed gravity values. Consequently, the data were reduced using the technique of Bull and Hardy (1956) in which the difference in the corrected values of gravity at the bedrock stations on opposite ends of each traverse was assumed to be the regional gradient and was distributed linearly along the traverse line according to the distance from the bedrock.

Bouguer Anomalies

The gravity deficiencies which result from making the required corrections to the observed data are not Bouguer anomalies in the strict sense in that they are based on relative values of gravity rather than on absolute values. However, they will be referred to as "anomalies" in this report for the sake of convenience.

In estimating the ice thickness along each profile, the following procedure has been adopted. At the bedrock stations on either end of the traverse the ice thickness was known to be zero. The difference in the anomalies between these points was attributed to the regional gradient and distributed linearly along the line. The remaining "anomalies" resulted from the assumption that all of the underlying material was of density 2.79 g/cm^3. It has been assumed that the deficiency at the glacier stations resulted from the lower density of the ice.

The contribution of gravity, Δg, at a station due to an infinite slab of material, thickness h, with density ρ can be found from the following equation (Heiskanen and Vening Meinesz, 1958):

$$\Delta g = 2\pi G\rho h$$

where G is the universal gravitational constant (6.673×10^{-8} $dynes/cm^2/g^2$). Solution of this equation for h, letting $\Delta g = 1.0$ mgal, yielded a value of 14.16 m/mgal.

Using this factor, the ice thickness at each station was calculated. Station gravity and all reduction data are given in Appendix D. The maximum gravity deficiency was 30.89 mgals at flag 7, line 8 which yields an ice thickness of 437 m. The computed valley profiles are presented in Figures 10 and 11. Figure 12 shows the topography of the floor of the valley as determined from the survey and gravity data.

Accuracy of Values

Errors in the gravity values from which the ice thicknesses have been determined arise from two sources: (1) errors in the corrections and (2) errors in the basic assumptions.

There are five possible sources of error in the corrections: (1) variations in bedrock density, (2) error in the determination of the relative elevations of the stations, (3) incorrect relative horizontal coordinates for the gravity stations, (4) errors in the terrain

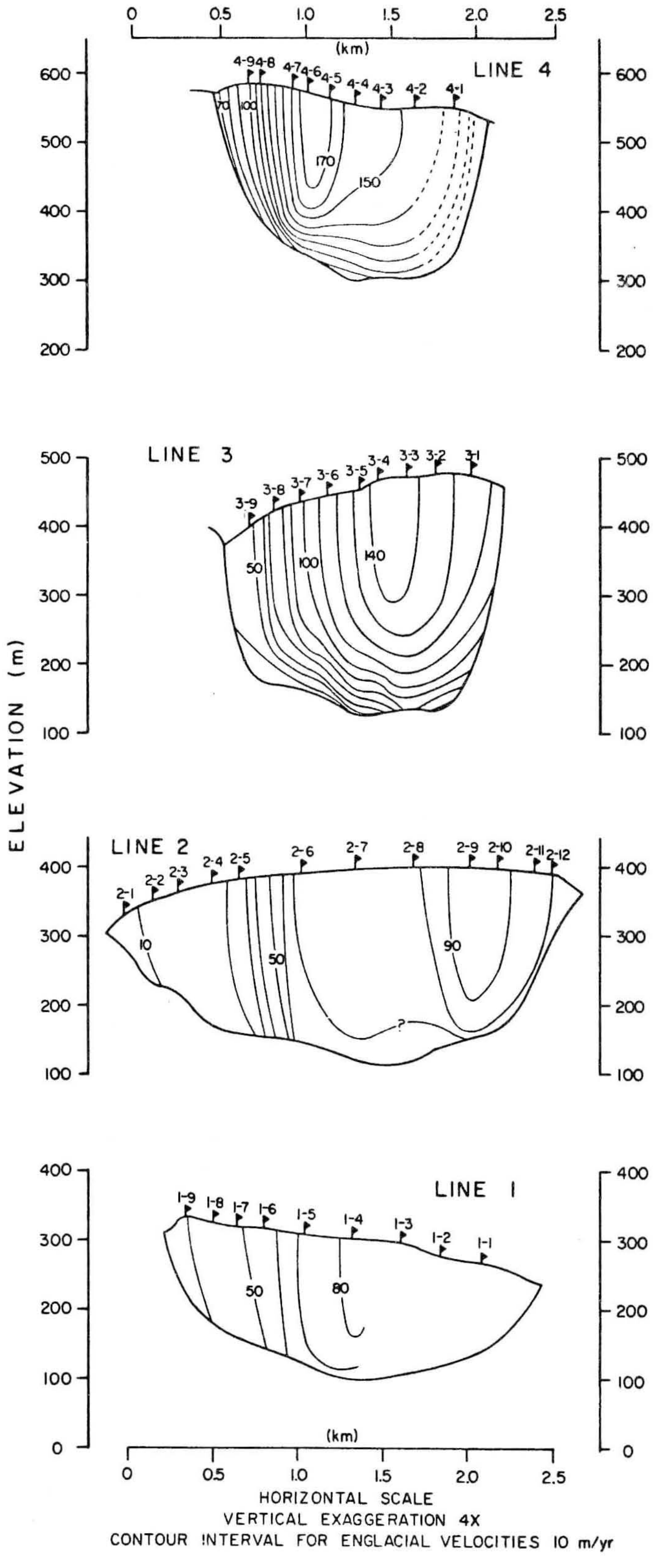


Fig. 10 - Profiles along lines 1-4 with the ice thicknesses based on 1965 gravity data and englacial velocities calculated from the flow law of ice (see Chap. VI).

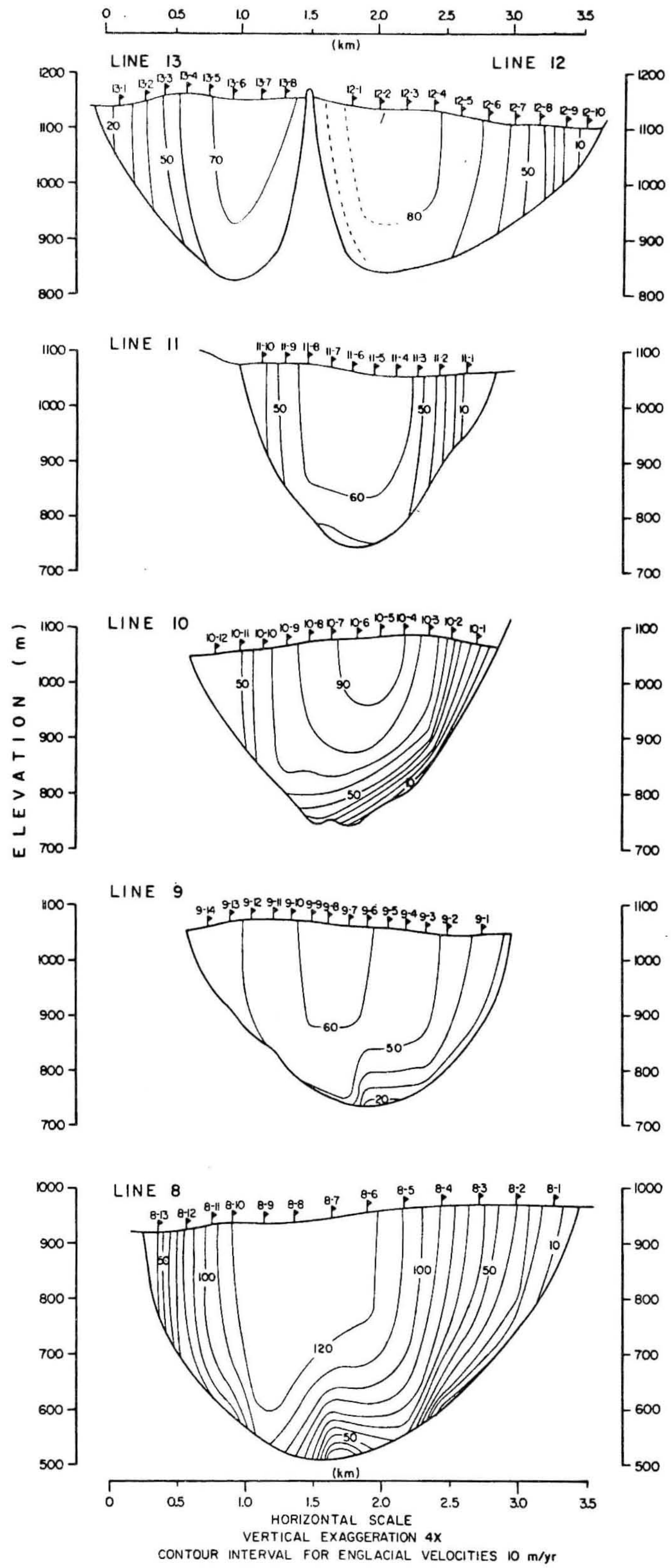


Fig. 11 - Profiles along lines 8-13 with the ice thicknesses based on 1966 gravity data and englacial velocities calculated from the flow law of ice (see Chap. VI).

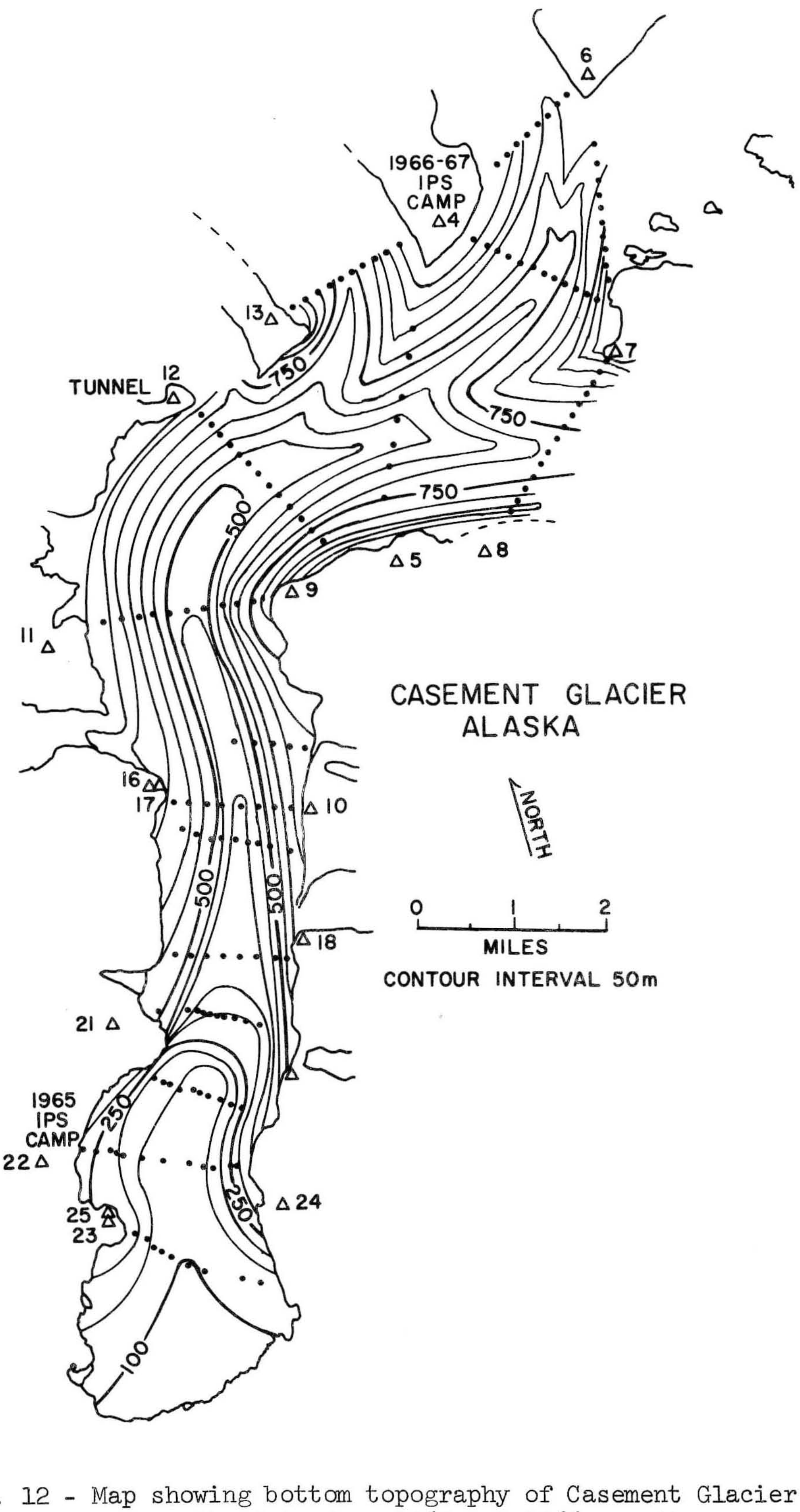


Fig. 12 - Map showing bottom topography of Casement Glacier based on gravity data from 1965 and 1966 gravity surveys.

corrections, and (5) error in the determination of station gravity and application of the drift correction.

The bedrock density may vary from place to place because of lithologic and structural changes, but for the sake of simplification, a constant density of 2.79 g/cm^3 was used in all the calculations. An error in the density of $\pm$ 0.1 g/cm^3 would produce an error of 0.30 mgal in the Bouguer correction (4 m of ice).

The errors in the differences in elevation between the bedrock and ice stations is $\pm$ 1.0 m. This would introduce a possible error of 0.19 mgal (3 m of ice).

The relative horizontal positions of the stations on the ice are accurate to the nearest $\pm$ 0.5 m and those on the bedrock to $\pm$ 5 m. Although there is a possible error of 2° in the orientation of grid north relative to true north, the error in the latitude correction is less than 0.01 mgal and is considered to be negligible.

The terrain corrections are subject to the largest error because the rugged topography makes their evaluation difficult. The mean terrain correction is 1.58 mgal. Although it is extremely difficult to judge the accuracy of the terrain corrections, the maximum error probably does not exceed 20 per cent, making the mean value of terrain corrections to be in error $\pm$ 0.32 mgal (5 m of ice).

Errors of observation in the determination of station gravity and applying the drift correction do not exceed $\pm$ 0.05 mgal.

The two basic assumptions which introduce error are: (1) the assumption that the difference in relative gravity at the opposite ends of a traverse results from a linear regional gravity gradient, and (2) the assumption that the ice thickness may be calculated using the infinite slab equation. The assumption involved in estimating the regional gradient required a maximum adjustment of 1.65 mgal/km (along line 13) and had a mean value of 1.04 mgal/km. This difference, which was attributed to the gravity gradient, could have been the result of changes in the bedrock density or errors in the calculation of the terrain correction at the bedrock stations rather than the gravity gradient. Any error introduced by this correction probably does not exceed $\pm$ 1.04 mgal.

Corbató (1965) has pointed out that the infinite slab formula tends to underestimate the true ice thickness. He has computed differences which average about 3 mgal between the infinite slab and his three-dimensional model. However, the glacier for which Corbató made his calculations was much narrower than Casement and so the error from the infinite slab assumption is reduced and will not exceed 0.5 mgal.

Accepting all the errors as maximum possible, the maximum possible error amounts to 2.40 mgal which is equivalent to 34 m of ice or about 14 per cent of the average glacier thickness.

CHAPTER IV

MASS-BUDGET STUDIES

Because of the myriad of terms used in mass-budget analyses, Meier (1962) proposed the adoption of a uniform set of terms to be used in reporting the results of glaciological investigations. Meier states:

> The difference between accumulation and ablation is termed the net budget. This quantity is the vital link between the climatic environment and the dynamic adjustment of the glacier to that environment; neither accumulation nor ablation matter individually. Therefore considerable attention is directed to a knowledge of time and space variations in net budget.

A budget year (used in this report interchangeably with glaciological year) is defined as that interval between the time when accumulation of new snow exceeds ablation over the whole glacier and the close of the ablation season the following summer when accumulation again exceeds ablation. In southeast Alaska, this break between successive budget years occurs in late summer or early autumn. Obviously, the beginning of the budget year varies from year to year with changes in the climatic conditions. The ablation season does not begin at all elevations on the same day. Indeed, the snow line migrates up the glacier in the spring and back down the glacier in the fall. The most convenient method of dealing with this problem is to measure the seasonal mass loss in the ablation zone and the seasonal gain in the accumulation zone over the span of a glaciological year.

The net budget of a glacier is determined as the difference between the accumulation and the ablation. A positive net budget indicates that the accumulation exceeded the ablation; a negative budget results when ablation exceeds accumulation; when the ablation and the accumulation are equal, the mass budget is considered to be in equilibrium.

Ablation

Introduction

Meier (1962) defines ablation as the material removed from a glacier by melting, evaporation, calving, wind erosion, and the loss of snow and ice by avalanches. Calving from Casement Glacier is restricted to a small section where the edge of the glacier forms a dam, impounding meltwater in a small, ice-free tributary valley and also along a short portion of the terminus where a proglacial lake forms annually in the spring. The amount of ice lost by calving is negligible compared with losses by melting and, therefore, an assessment of its mass has not been attempted for this budget study. The loss by bottom melting is estimated to be 0.5 $g/cm^2/yr$ and it is not considered in the analysis. The most important factor in ablation on Casement Glacier is surface melting.

The amount of snow and ice lost from the ablation zone of the glacier in a glaciological year is called the total net ablation. Neglecting bottom melting and calving, this can best be determined by measuring the lowering of the surface at a large number of points on the glacier. A study to evaluate the relative contributions of different meteorological factors in melting the ice was conducted in 1967; the results are presented and discussed in Chapter VIII of this report.

Method of Measuring Ablation

The most common method of measuring ablation is to measure the lowering of the glacier surface relative to a fixed marker, usually a stake drilled into the ice. The measured ablation is then multiplied by the density of the ice or snow to give the ablation in terms of water equivalent or mass. Seasonal ablation was measured at each of the survey markers shown in Figure 3.

The marker poles were placed in holes drilled into the ice. The height of the pole after insertion into the hole was recorded, as was the snow depth, if any snow remained. The pole heights were remeasured whenever time permitted later in the season. The holes were redrilled whenever more than 2.5 m of pole projected above the surface of the glacier.

Accuracy of Stake Measurements

The accuracy of total ablation measurements depends on the number of stakes in the network, the amount of daily ablation, and the type of prevailing weather. Schytt (1962) suggests that for reliable ablation studies, a stake density of ten to twenty stakes per square kilometer is desirable. For Casement Glacier, this would have meant a network of about 1,500 ablation stakes, a quantity that would have been extremely difficult to maintain. The errors involved in stake measurements of ablation are discussed in detail in Chapter V of this report. Probably the error in seasonal ablation, as measured by the stake method, is less than 20 per cent. Vallon (1968) has pointed out that, when the flowlines are not parallel, the observed values of ablation will be in error unless the effect of the longitudinal strain-rate on the emergence is considered. Because of a lack of data on the longitudinal strain-rate, corrections for this factor could not be made.

Accumulation

Introduction

Winter accumulation on a glacier usually consists of snow and hoar-frost, snow being the more important on a temperate glacier. The accumulation may vary quite considerably over the surface of a glacier. The main factors controlling snowfall are elevation, topography of the glacier surface, and prevailing wind directions. Normally, snowfall increases with elevation. For the same elevation, more snow accumulates on a concave surface than on a convex surface. Because of the marked lateral variations in accumulation, it is necessary to measure the snow depth at a large number of points on the surface of the glacier.

Method of Measuring Accumulation

The accumulation measurements on Casement Glacier were made using snow pits and snow-depth probes. Ideally, the best results are obtained from a large number of snow pits; however, in order to economize time and effort, the thickness of the 1966-1967 snow layer was measured with aluminum avalanche probes along transverse and longitudinal lines. In each tributary that was examined, one snow pit (Fig. 13), in which a density profile was made, was dug in the center of the accumulation basin. With the previous summer's crust visible in the pit, the probe was rammed into the snow near the pit to get the "feel" of the resistance offered by the 1966 summer crust. This was used to determine the snow depth at other locations where pits were not dug. Snow-depth soundings were made at 75 m intervals on lines transverse to the flow at the site of the snow pit and longitudinally, from the pit to the firn line.

The locations of the snow pits and the snow-depth profiles are shown in Figure 14. Neither time, weather, nor snow conditions permitted as extensive a snow-depth survey at the end of the ablation season as had been desired. The available data, however, have been extrapolated to include the unsurveyed areas of the accumulation zone, in order to calculate the approximate mass of the snow remaining in the névé basins at the end of the ablation season, the quantity Meier (1962) defines as total net accumulation.

Mass Budget for the 1966-1967 Glaciological Year

Introduction

In order to estimate the net budget total, the mass of snow and ice lost from the ablation zone in the 1967 ablation season minus the mass of new snow left at the end of the 1966-1967 budget year, the glacier has been divided into four sections on the basis of elevation (Fig. 15): (1) the section from the terminus to the first icefall, (2) the section

Fig. 13 - Photo of snow pit dug in 1966 showing technique for measuring the variation of snow density with depth.

Fig. 14 - Map of upper portion of Casement Glacier showing the locations of the snow pits and the snow depth profiles made in September, 1967.

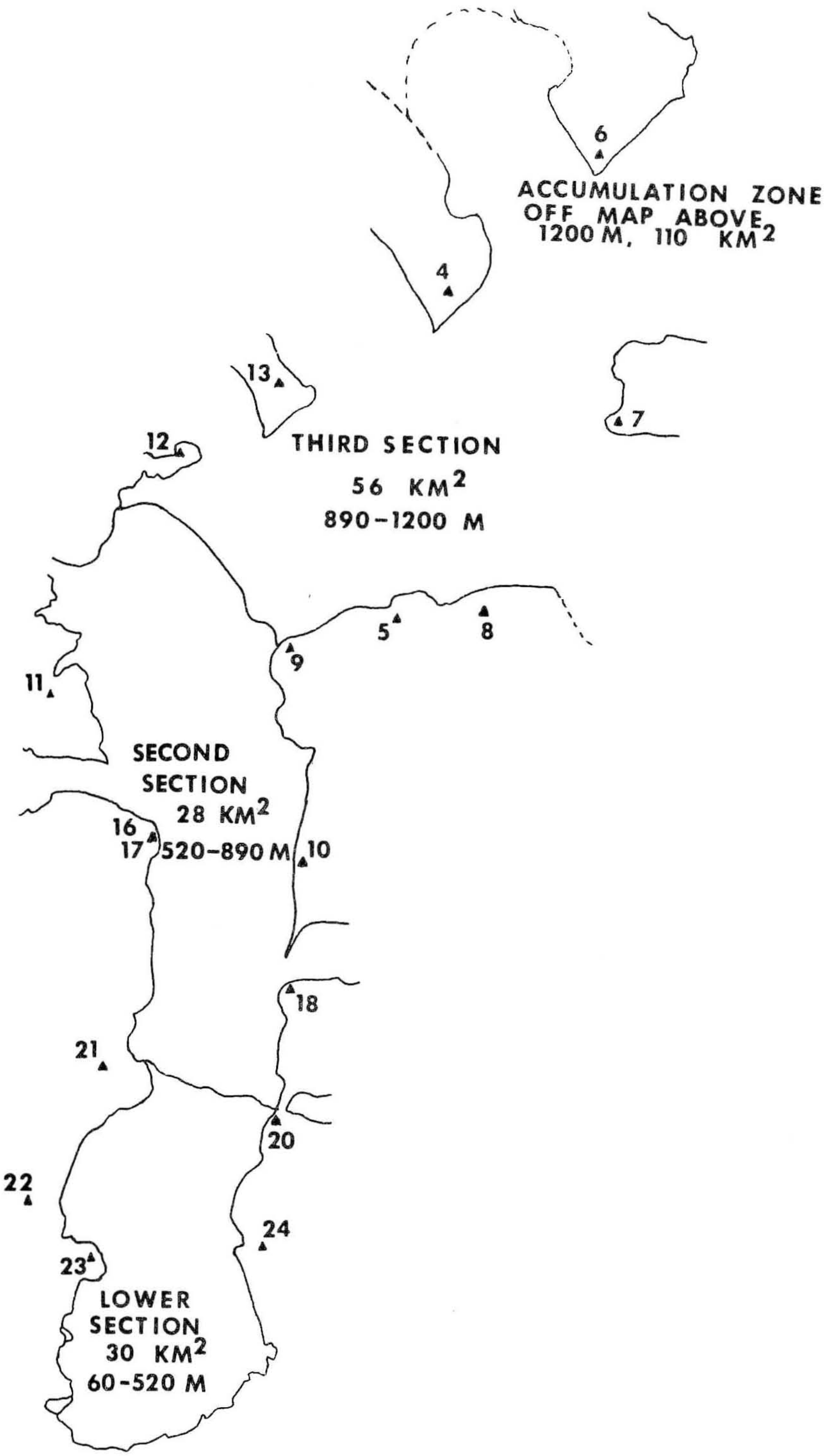


Fig. 15 - Map of Casement Glacier showing divisions for mass-budget studies.

bounded by the first and third icefalls, (3) the area from the third icefall to the firn line, and (4) the areas above the firn lines for each of the tributaries.

Lower Section

This 30 km^2 portion of the glacier lies between 60 m elevation at the terminus and 520 m at the first icefall. During the first season, ablation was measured at three stake lines (Fig. 3). The specific ablation rates vary quite markedly over this area, according to the thickness of the debris cover. In order to calculate the mass lost, the per cent of the total area of ice that was debris-covered was estimated from the 1965 aerial photographs Then, two ablation rates were calculated, one for debris-covered ice and one for clean ice, and a weighted value of ablation was calculated based on the ratio of the two kinds of surface. Complete ablation figures for this section of the glacier are available only for the 1965 summer, when the estimated total net ablation was $150 \pm 30 \times 10^9$ kg. The $\pm 30 \times 10^9$ kg represents an error of 20 per cent. At the stakes in line 2, the total net summer ablation was 10 per cent greater in 1967 than in 1965. Assuming that this 10 per cent increase can be applied to the whole year, the total net loss from this section for the 1966-1967 glaciological year is estimated as $165 \pm 41 \times 10^9$ kg.

Second Section

The second section (28 km^2) incorporates that portion of the glacier between 520 m and 890 m elevation. The seasonal ablation rate applied to this section was derived from ablation measurements made during the 1966-1967 budget year on the stakes in lines 4 and 5 (see Fig. 3). The mean rate of 175 g/cm^2 ($1.75 \times 10^3 kg/m^2$) gives a net loss of $50 \pm 10 \times 10^9$ kg.

Third Section

The section of the glacier (56 km^2) between the third icefall and the firn line is relatively flat, with only minor icefalls disrupting the gently sloping surface. The elevation over this portion ranges from 915 to 1220 m and averages about 1050 m. Using the mean annual ablation rate of 120 g/cm^2, as determined at lines 8, 9, 10, 11, 12, and 13, the loss over this section of the glacier for the budget year 1966-1967 was calculated to be $70 \pm 14 \times 10^9$ kg.

Accumulation Zone

The accumulation for Casement Glacier collects in seven separate cirques and across a divide where the accumulation is shared with Davidson Glacier, which flows to the northwest towards Lynn Canal (Fig. 1). The firn line was farther upglacier each successive summer.

The mass of snow remaining from the 1966-1967 accumulation has been estimated from the pit and probe studies (Figs. 16,17) made in early September 1967. On September 11, 1967, a new layer of snow in the accumulation zone was thought to indicate that the ablation season was just about over, marking the close of the 1966-1967 budget year. It is assumed, therefore, that the measured values of snow depth for the calculation of the net accumulation are not in error. However, it must still be recognized that only a small portion of the accumulation zone was sampled and that the required extrapolation is tenuous.

The mean apparent accumulation in the névé basins is estimated as 45 g/cm^2. This mean accumulation extrapolated over the catchment basin (110 km^2) gives $50 \pm 12 \times 10^9$ kg total net accumulation.

Summary

The total net ablation for the 1966-1967 budget year for Casement Glacier was $285 \pm 44 \times 10^9$ kg, while the total net accumulation was only $50 \pm 12 \times 10^9$ kg, resulting in a negative budget of $235 \pm 56 \times 10^9$ kg. The results are summarized in Table 5.

TABLE 5

CASEMENT GLACIER, MASS BUDGET 1966-1967

Elevation interval (meters)	Area (km^2)	Net budget ($\times 10^9$ kg)
60-520	30	-165 ± 41
520-890	28	$- 50 \pm 10$
890-1200	56	$- 70 \pm 14$
1200+	110	$+ 50 \pm 12$
60-1200+	224	-235 ± 56

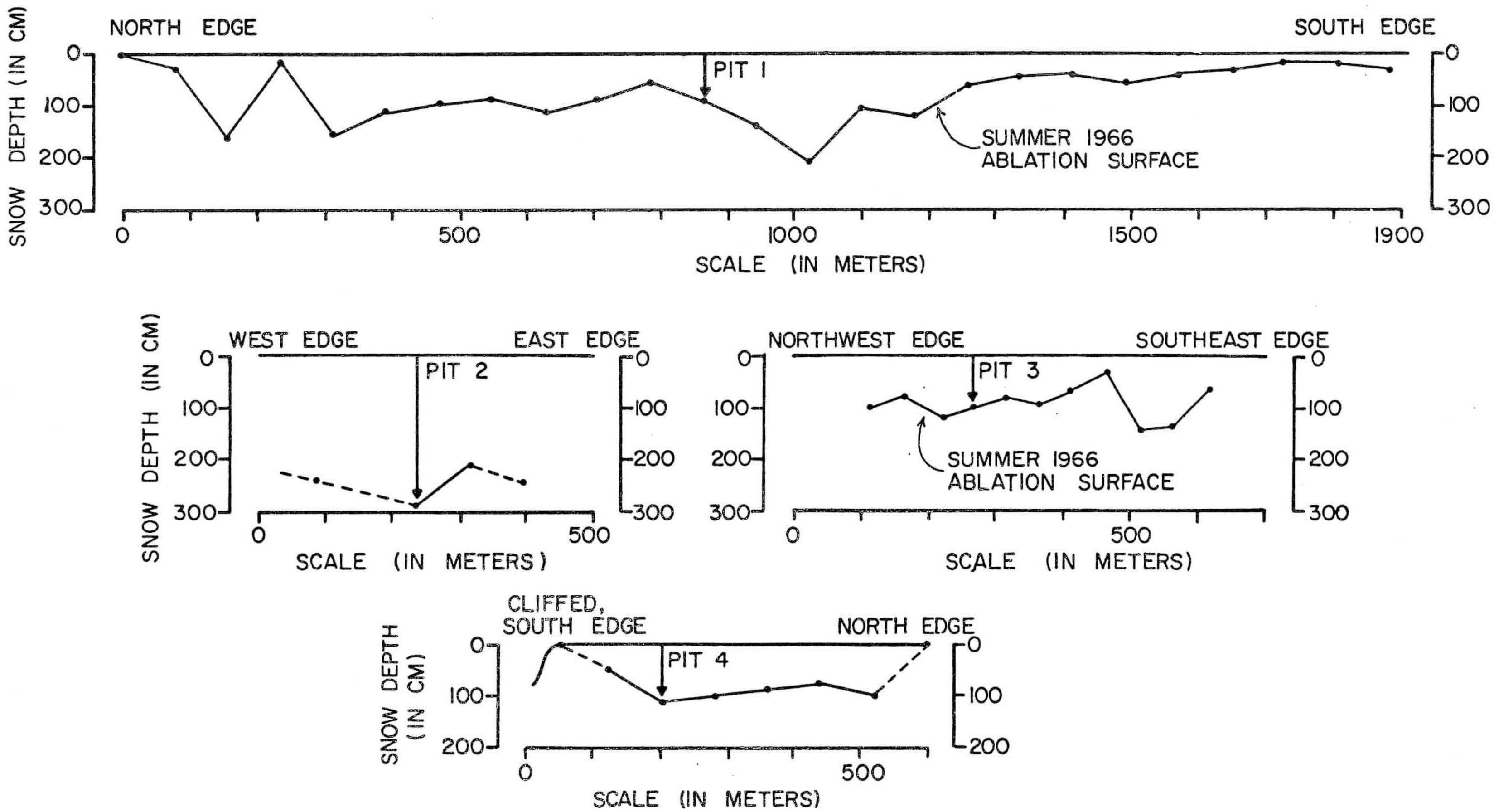


Fig. 16 - Snow depth profiles measured transverse to the flow line at the sites of the snow pits dug in September, 1967. See Figure 17 for longitudinal profiles.

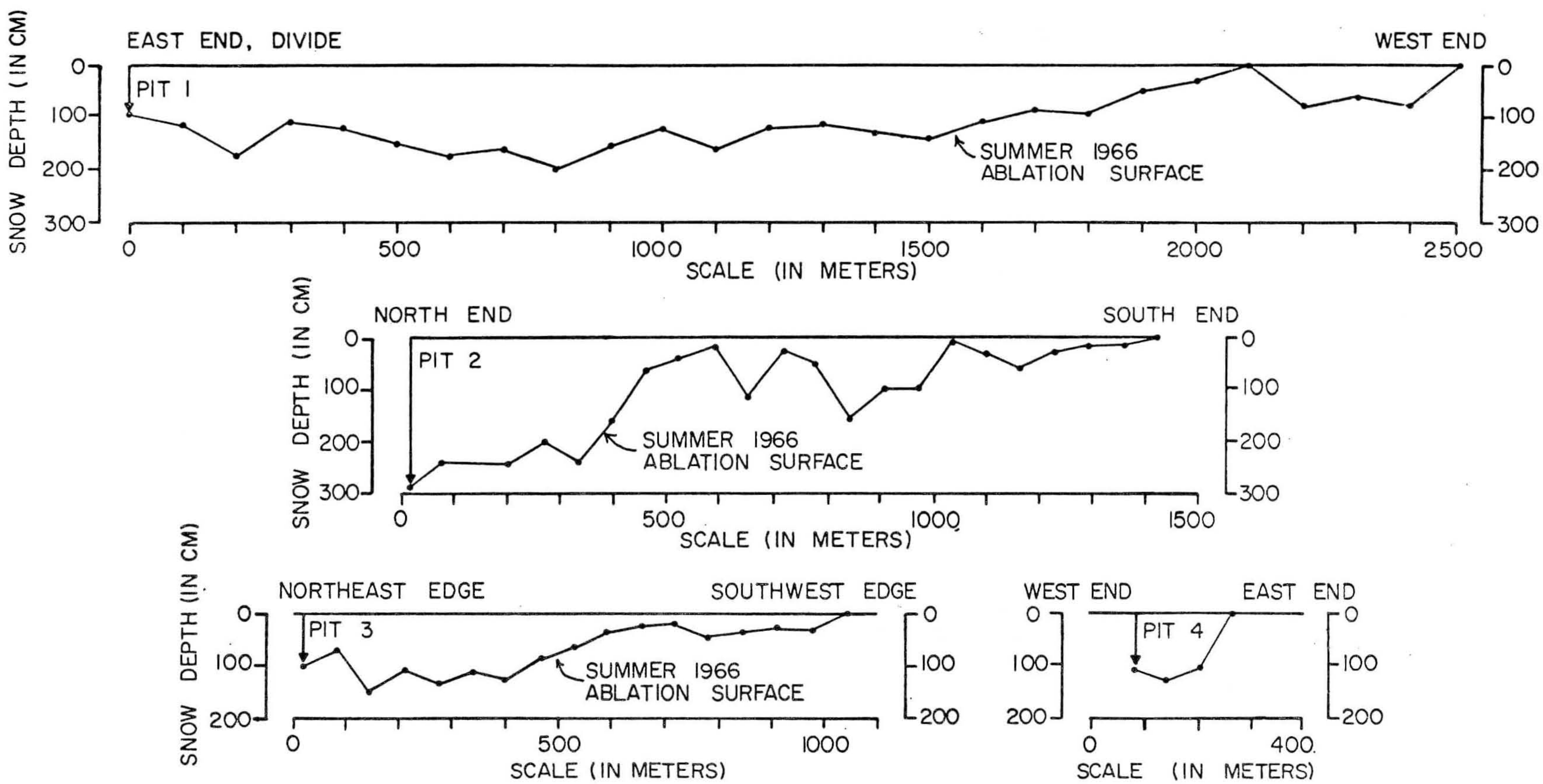


Fig. 17 - Longitudinal snow depth profiles made from the sites of the snow pits to the firn lines, 1967 season.

Discussion

The mass budget of a glacier depends upon meteorological conditions. A more positive budget can be effected in four ways: (1) increased wintertime accumulation, (2) decreased summer ablation, (3) reduced winter ablation, or (4) increased summer accumulation. For any condition, the result on the mass budget would be the same.

In order to compare the meteorological conditions for the three field seasons with the observed position of the firn line at the end of each season, the weather records for the nearest reporting station with the longest records, Juneau, were consulted. Temperature and precipitation statistics of the mean annual summer (May, June, July and August) and winter (November, December, January, and February) values are presented in Table 6.

TABLE 6

TEMPERATURE AND PRECIPITATION STATISTICS
FOR JUNEAU, ALASKA

	Temperature statistics (^{o}C)			Precipitation statistics (mm water)		
	Mean ann.	Mean sum.	Mean wint.*	Mean ann.	Mean sum.	Mean wint.*
1958-67	4.5	11.1	1.2	1458	431	481
1965	4.1	10.2	-4.5	1216	355	584
1966	2.9	10.6	-2.1	1482	466	339
1967	2.9	11.1	-3.0	1481	395	449

*Winter statistics were calculated using the Nov. and Dec. data from the preceding year.

The conditions were best for a balanced budget in 1965. In that year the mean summer temperature was lowest, the mean winter temperature was lowest, and the winter precipitation exceeded the ten-year mean by 21 per cent. This combination of factors resulted in a firn line 180-240 m below the elevation of the firn lines of the two subsequent years.

From the statistics it would be difficult to predict in which of the two succeeding years the firn line would have been higher. Winter precipitation was higher in 1965-1966; temperature was higher in the summer of 1967. The effect of increased summer melting in 1967 (at line 11 ablation was 10 per cent greater in 1967) due to higher temperatures was more than enough to offset the larger amount of winter precipitation during the 1966-1967 winter, resulting in the highest firn line of the three seasons.

Although mass budget changes in a single glacier can be related to annual fluctuations of the controlling meteorological parameters, it does not necessarily follow that the behavior of neighboring glaciers can be predicted. Climatic fluctuations are widespread enough so that conditions would change uniformly over a region like Muir Inlet, yet each glacier responds differently to changes in regime. This is because of the individual morphological differences between the glaciers. Some have very small ablation zones with large catchment basins; others may have almost all of their surface area below the firn line. Thus, each glacier responds individually, according to its morphology, to fluctuations in climate. A classic example of this situation is found near Juneau where Lemon Creek Glacier is retreating and Taku Glacier, only a few miles away, is advancing because over 80 per cent of its surface lies above the firn line (Marcus, 1964).

Therefore, extrapolation of Casement Glacier mass budget results to other glaciers in Muir Inlet is risky because of their large losses by calving and bottom melting from contact with ocean water. Certainly, a mass budget study is not necessary to recognize that the other glaciers have negative budgets; however, to make an accurate assessment of their budgets, one would have to study each of them on an individual basis.

Rate of Retreat of Casement Glacier Related to Twentieth Century Climatic Trends

Goldthwait (1963) has estimated that between 1892 and 1942 the firn line in the Muir Inlet area rose about 300 m. The result has been the dramatic retreat of the glaciers in the inlet. The budget conditions that are reflected in the behavior of the terminus are responsive to changes in climate. Marcus (1964) has determined that the climatic variables that exert the most influence on the budget of a glacier are the thermal effectiveness (number of positive degree days in the ablation season) and accumulation season precipitation. Unfortunately, the year-to-year changes of these parameters are not available. In lieu of this, the data from the weather station at Juneau (115 km to southeast) have been used in this analysis.

The monthly mean temperatures of the threshold months--April, May, September, and October--should provide some idea of the thermal effectiveness. Marcus (1964) did not find any direct relationship between the length of the ablation season and the annual budgets. However, the longer the ablation season, the greater the thermal effectiveness, and so a warming in the threshold months would both lengthen the ablation season and increase the thermal effectiveness. Marcus (1964) computed five-year running means from the temperature data for the threshold months. His data were extended so that the graphs included the records up to 1967.

The second important element upon which a glacier's budget depends is winter precipitation (Marcus considered this to be the precipitation during the period from October through March). The trends in winter precipitation over the last 65 years have been computed as five-year running means.

The rate of retreat of Casement Glacier by decades has been determined by Goldthwait (1966) from a large number of old photographs (see glacial history, Chapter I). The retreat of Casement Glacier has been related to the climatic trends determined by Marcus.

It must be considered that the two factors, winter precipitation and thermal effectiveness, do not have the same response times. An increase in thermal effectiveness has an immediate as well as long range effect on the rate of retreat of the terminus. Whereas, there is a time lag of a number of years for the glacier to respond to changes in accumulation. This response time depends on the size of the glacier. For Casement Glacier the response time is about 10 years. As a result, the behavior of the terminus, when considered as a function of the meteorological conditions for a single budget year or even for a five-year period, may not be representative of the effect of the observed set of conditions; but may, instead, reflect the budget conditions from several years prior to those of the period of observation.

<u>1910-1920</u>

The retreat rate during this period was the second lowest of all the decades for which the rate has been determined, 30 m/yr. The climatological data show a general decrease in temperatures through this period except for a brief interval in the midteens. The winter precipitation decreased to a minimum in 1910 and remained low until after 1915. However, the threshold month temperatures which were also low tended to counteract the effect of the low accumulation.

1920-1930

This interval is marked by a dramatic increase in the rate of retreat from the last decade, from 30 m/yr to 95 m/yr. Climatologically, the reason for this is not readily apparent. There is an overall increase in the mean temperatures for the months of April and October which should have a negative influence on the budget. The winter precipitation did not vary much during the decade. The increase in the rate of retreat probably resulted from the increase in thermal effectiveness over the decade combined with the low accumulation of the previous decade.

1930-1940

During this period the temperatures of the threshold months increased markedly, while the winter precipitation remained fairly constant. The increase in threshold month temperatures would suggest a longer and more effective ablation season. Since the precipitation did not increase significantly during this nor the previous decade, the retreat rate was higher than during the interval from 1920-1930, increasing from 95 to 98 m/yr.

1940-1950

The climatic conditions during the first part of this decade are marked by a carry-over of the increases in the threshold month temperatures from the previous decade. This was followed by a general decrease in temperatures all over the Pacific Northwest which resulted in the advance of many glaciers. However, the effect of the extremely negative budgets from the previous decade and the first few years of this decade (1940-1950) dominated the behavior of the terminus and the rate of retreat increased to 113 m/yr.

1950-1960

The running means for the temperatures of the threshold months in the spring show marked increases during this decade, while those of September and October show little variation from the beginning to the end of the period. The winter precipitation did not change significantly from the preceding decade. This set of conditions would suggest an increase in the rate of retreat. However, Goldthwait (1966) has reported a mean retreat of 24 m/yr during this decade, the lowest rate for any decade since 1910. The reason for this apparently anomalous behavior lies in the fact that during the last half of the preceding decade, 1940-1950, conditions were favorable for less negative budgets. As a result of the time lag between a change in budget conditions and the behavior of the terminus, their effects were not experienced at the terminus until a decade later. Although the conditions during the period from 1950 to 1960 probably did result in a higher mass loss per year than in previous years, because of the increased discharge, the rate of retreat was decreased.

1960-1967

The moving averages of the temperatures during this time interval increased for the fall threshold months and decreased for the spring threshold months. The winter precipitation increased during this period. Although no figure has been given for the rate of retreat of the terminus from 1960-1967, it is estimated to be between 75 and 100 m/year. This increase in the rate of retreat is attributed to the response of the glacier to the lean budget years during the last two-thirds of the preceding decade 1950-1960.

CHAPTER V

SHORT-TERM ABLATION STUDIES

Introduction

During the summers of 1965 and 1967 ablation at stakes was measured daily in an attempt to relate daily ablation rates to meteorological conditions. In 1965 ten wooden stakes, 92 cm long and 0.65 cm in diameter, were emplaced along the margin of the glacier near the 1965 camp at an elevation of 330 m with observations being made of the stake heights on most evenings from 3 July to 11 August. A similar study was conducted near the upper glacier camp in 1967 at an elevation of 1,050 m; observations were made almost daily from 18 July to 7 September.

Problems in Measuring Daily Ablation

Daily ablation is usually measured by the surface lowering method. In this method, a measurement is taken from the top of the stake to the glacier surface, which, because of its irregular topography, is poorly defined. To standardize the measurements and eliminate as much error of measurement as possible, the ice surface was defined as that surface even with the bottom of an ice axe laid across the ice at the stake. The accuracy is limited by irregularities on the glacier surface and by ablation around the stake. The error in the measured value of ablation is taken to be ± 0.5 cm (Keeler, 1964).

The surfaces produced by ablation are quite different on sunny days and cloudy, rainy days. On a sunny day the strong radiation makes the surface take on a weathered appearance as the ice melts preferentially along the crystal boundaries reducing the density of the surface ice. Nobles (1960) refers to this type of surface as "weathering rind". Because of the melting of the crystal boundaries, the crystals in the surface ice can be scraped off easily with an ice axe.

During periods of wind and rain with low radiation, the small-scale relief on the surface is smoothed out and the ice becomes glazed and slippery. Structural features such as foliations and fractures once again become visible. When a period like this follows a period of intense radiation, the measured ablation will be much higher than the actual ablation because the less dense "weathering rind" will account for a portion of the surface lowering. Conversely, the measured ablation for a day with high radiation following a period of turbulent, rainy weather, would be too low, because much of the ablation takes place along the crystal boundaries below the surface without lowering the surface in true proportion to the actual amount of ablation. Fortunately, during the course of a summer, both kinds of weather occur and the errors in measuring the ablation tend to cancel each other over longer periods.

Results of the Daily Ablation Studies on Casement Glacier

Lower Glacier, 1965

There were several extended periods of sunshine during the summer which are reflected in the daily ablation data: 6-13 July, 27 July-1 August, and 4-9 August. From 6-13 July there were six consecutive days on which the mean ablation exceeded 9.0 $g/cm^2/day$. The maximum observed ablation for one day was 12.8 g/cm^2 at pole 10 on 11 July. The mean ablation for all the stakes on that day was 11.2 g/cm^2. Even on a day with completely overcast skies the ablation was still about 4.5 $g/cm^2/day$. The minimum mean ablation occurred on 3 August when it was 3.2 g/cm^2.

Upper Glacier, 1967

In 1967 the three main intervals with strong, direct radiation were 22-25 July, 3-6 August, and 15-17 August. The maximum mean ablation for the whole period was 5.1 g/cm^2 on 24 July. The lowest mean ablation occurred on 21 August and was 0.4 g/cm^2.

Relationship between Weather and Ablation

26 July and 18 August were two days following periods of strong radiation. Although there was only weak direct radiation on each of these days, the measured ablation was equal to that on days with 10-12 hours of bright sunshine. On 19-20 August the precipitation increased in intensity, but the measured ablation decreased. The measured ablation for 15 August, a day with 9.25 hours of bright sunshine, was only slightly more than that for the preceding day on which there was no sunshine.

The most general statement that can be made about the complex relationship between weather and ablation is that when weather provides more heat energy at the surface of a temperate glacier than it is carrying away (positive heat balance), ablation will occur. Unfortunately, solving the heat balance equation for the various contributions of the different terms is difficult and requires a moderately extensive meteorology program. It would be more useful if the ablation could be related to a few, easily measured parameters.

The most obvious index to be considered is air temperature. This is an easy quantity to measure and it is commonly regarded as a measure of the heat energy in the ground layer of the atmosphere. Figures 18 and 19 are plots of cumulative ablation against cumulative glacier degree days (mean daily air temperature °C = glacier-degree days). From the two graphs it is apparent that the relationship between daily ablation and air temperature is nearly linear. The relationship between ablation and other meteorological parameters is shown graphically in Figures 20 and 21.

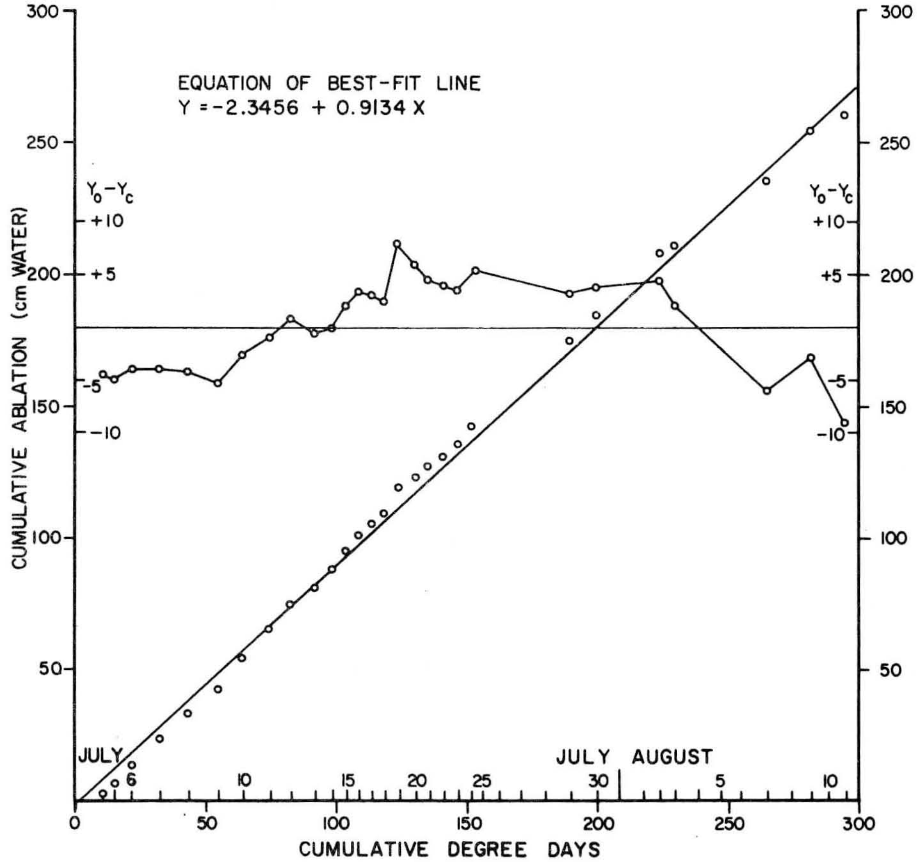


Fig. 18 - Plot of cumulative days versus cumulative ablation and deviations from best-fit straight line, lower glacier, 1965.

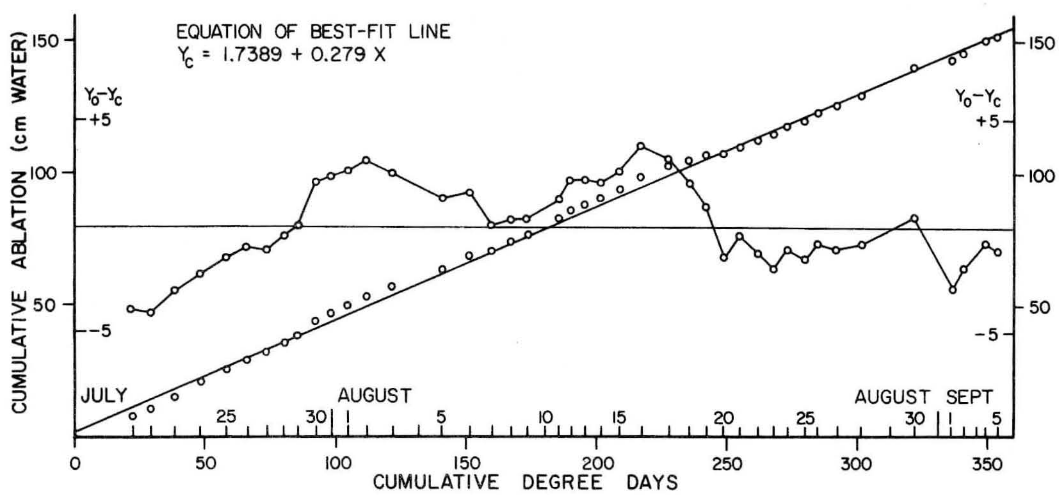


Fig. 19 - Plot of cumulative degree days versus cumulative ablation and deviations from best-fit straight line, upper glacier, 1967.

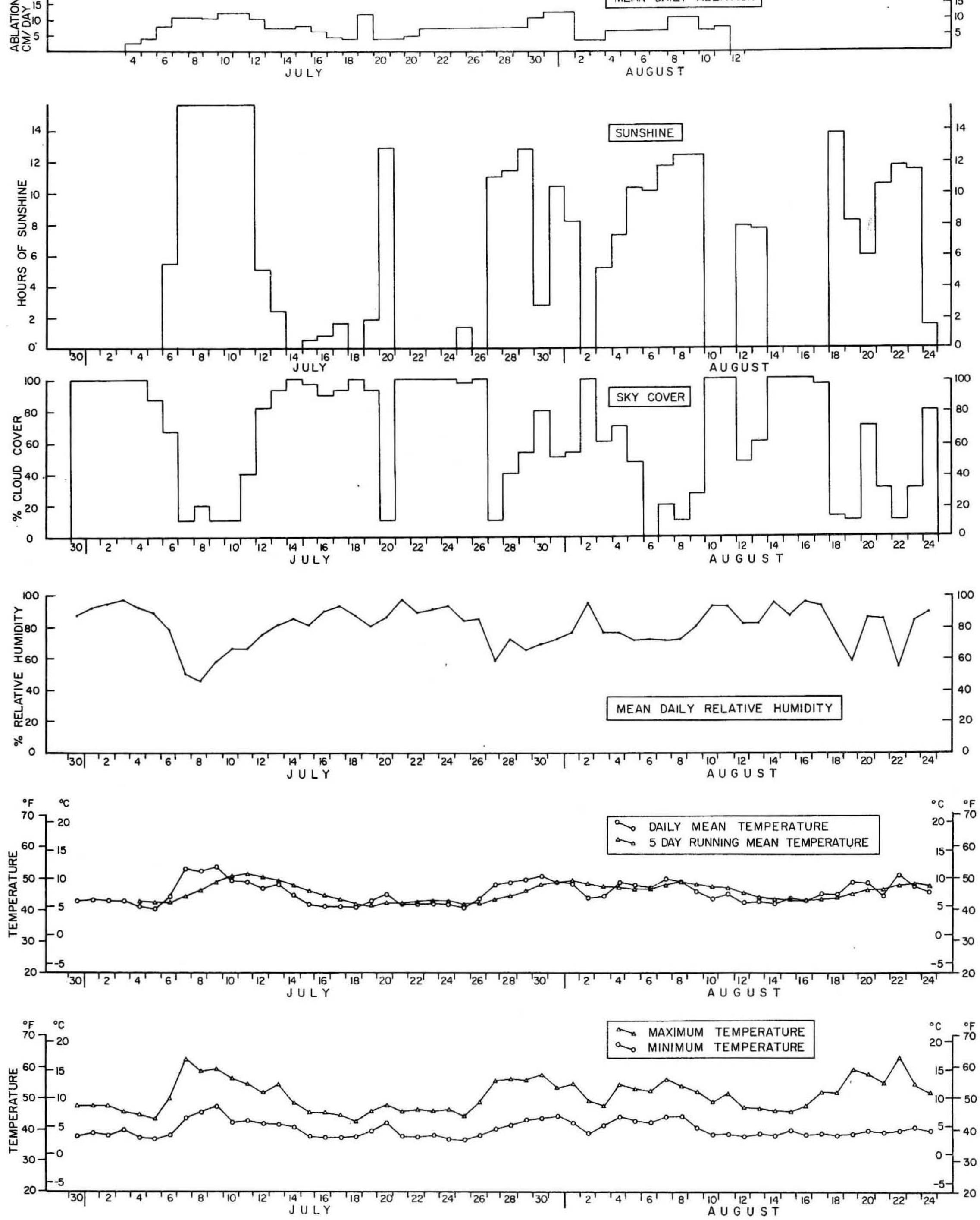


Fig. 20 - Daily ablation and meteorological conditions at Lower Glacier Station, Casement Glacier, 1965.

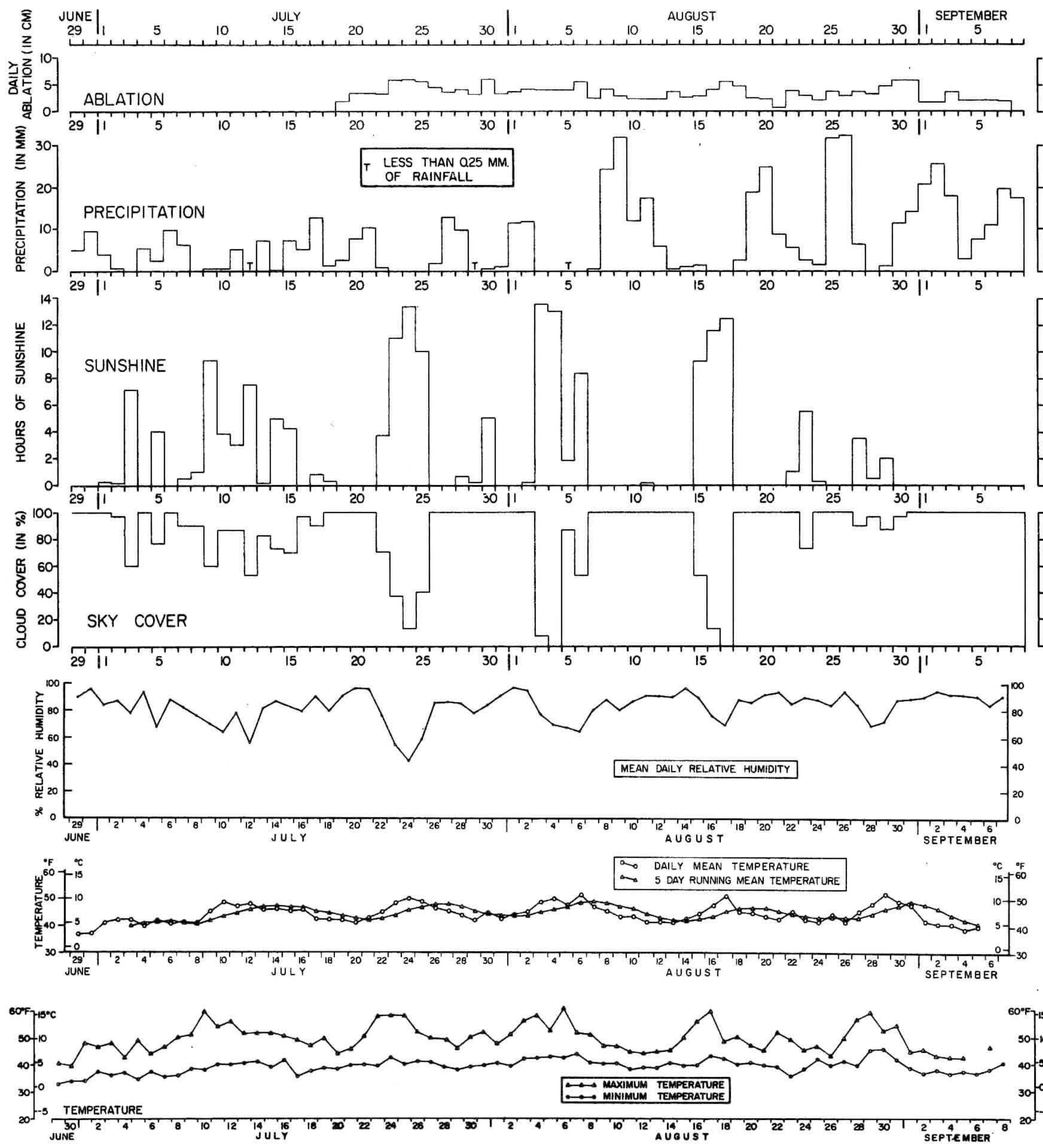


Fig. 21 - Daily ablation and meteorological conditions at Upper Glacier Station, Casement Glacier, 1967.

Comparison of the Two Studies

From the two plots of ablation versus degree days, it can be seen that the slopes of the best-fit lines, and, thus, the dependence of ablation on temperature, differ at the two locations. The reason for this difference in slope is that the combination of the turbulent transfer of sensible and latent heat components in the heat balance equation (see Chapter VIII, Short-Term Heat Balance Studies) decreases with increasing elevation.

The plots of the deviations from the best-fit straight lines for the data show extended periods of positive and negative values. The positive deviations correspond to periods with strong radiation and high temperatures. The negative deviations occur for periods during which there was weak radiation, low temperatures, and precipitation.

Discussion

Daily ablation measured by the straight edge-stake method, an ablatograph, or any other technique measuring ablation as a function of surface lowering will be in error. Ideally, the daily changes in density of the top few centimeters of ice should be measured so that a more accurate density value can be used in the calculation of the mass loss. Certainly, the measurement of surface lowering at stakes provides the most convenient way to measure surface ablation, but accurate measurement of the daily ablation requires a more sophisticated method. The most promising technique appears to be the measurement of discharge in supraglacial streams. A drainage basin on the glacier's surface is delimited and the discharge through the stream draining the basin is measured as a function of the dilution of a known concentration of salt solution. The measured discharge is converted to ablation/unit area.

There are a number of problems concerned with ablation which should be investigated: (1) a convenient, more accurate method for measuring short-term ablation should be developed, (2) the mechanics of the ablation process of polycrystalline ice should be better understood, and (3) the micrometeorology of the layer of air just above the surface of the glacier should be studied closely in order to better understand the exchange of energy at this ice-air interface.

The investigations of these problems would result in a better understanding of the ablation processes which would, in turn, aid future attempts to accurately measure daily mass losses due to ablation.

CHAPTER VI

ENGLACIAL VELOCITY PROFILES

Introduction

In the original proposal for glaciological work on Casement Glacier, one of the stated objectives was to drill a number of holes through the glacier and repeatedly measure their inclination to determine the variation of velocity with depth. These data were to be used for two purposes: the calculation of mass throughflow across a given cross section and the calculation of the trajectories of points initially on the surface of the glacier as they move through the ice.

Determination of Englacial Velocity Profiles

Hotpoint Drill

The drill design developed and used by Dr. R. Shreve (1962), Department of Geology, University of California, Los Angeles, was adopted for the construction of the drills to be used in the deep-drilling program. This design employs a nichrome wire heating element wrapped around a central copper core. The generated heat is conducted through the copper core to the tip which is in contact with the ice.

Using Shreve's plans, three electrical hotpoint drills were built in Columbus for use during the 1966 field season. Two of these drills burned out in trying to drill the first hole and the third could not be removed from the hole once it had been drilled successfully to a depth of 50 m. The three drills for the 1967 season were built under the close supervision of Dr. Shreve and were laboratory tested and found to be satisfactory. The drilling program in 1967 was more successful; however, the last drill was burned out in trying to reopen the holes for the second inclinometer survey. As a result, no englacial velocities were determined.

Computation from Nye's Equation

Because of the failure of the deep-drilling program to determine the englacial velocity distribution, the velocities had to be calculated from an equation derived by Nye (1952) based on Glen's flow law for ice (1952). This expression for the variation of velocity through a glacier is:

$$U_d = U_o \left(\frac{\rho g}{B}\right)^n \sin^n \alpha \, \frac{h^{n+1}}{n+1}$$

where

U_d = velocity at depth d

U_o = surface velocity

α = surface slope

d = depth to the point under consideration

B = constant equal to 0.164 bars $yr^{-1/n}$

n = constant equal to 3.0

ρ = density of ice, 0.9 g/cm^3

g = acceleration of gravity, 980 cm/sec^2

h = ice thickness.

Mathews (1959) has tested this equation with data from a deep hole in the Salmon Glacier and found that his data closely approximate Nye's equation for laminar flow. Therefore, it is probably valid to use this equation to calculate the englacial velocity profiles using the surface velocity data, the ice thicknesses from the gravity work, and surface slopes determined from the U. S. Geological Survey 1948 maps of the glacier.

The englacial velocities for all markers for which the ice thickness had been determined were calculated by computer, using a program written by Marangunić (1970). The program was designed to calculate the englacial velocities at 10 m intervals from the surface to the bottom. The results are shown in Figures 10 and 11.

The accuracy of the calculated englacial velocity profiles depends upon several assumptions. The first is that the englacial velocities may be calculated from Nye's equation. The fact that observational data (Mathews, 1959) fit values calculated from the equation suggests that the equation does give a good estimate of the englacial velocities.

Secondly, the assumed values of the flow law constants, B and n, must be considered. Wide ranges of values for these constants have been determined, because of their dependence on temperature. However, the values used in the equation best fit the present data for the flow law of ice at the pressure-melting temperature. Thirdly, the effect of inaccuracies in the values substituted into the equation, for the surface velocity, the surface slope, and the ice thickness, on the calculated englacial velocities must be considered. The horizontal coordinates of the stakes are accurate to ± 0.5 m. Assuming that all of the errors are at a maximum, then the total distance moved by the stake for the time interval between the surveys would be 1 m. This would produce an error of ± 2.5 per cent for stake 12-10 where the velocity was 4 m/yr and less than 1 per cent at the large number of stakes where the surface velocity was greater than 100 m/yr. The surface slopes have been estimated from the 1948 U.S.G.S. maps of the glacier and may be in error by ± 20'. This error could produce differences in the calculated velocity of 15 to 20 per cent. The largest error comes from the ± 14 per cent error in the calculated values of the ice thickness. A change of the value of h by 14 per cent would greatly affect the calculated values of the sliding velocities as the velocity is a function of h^{n+1}. It must be recognized, therefore, that the calculated values of the englacial and bottom velocities are but an approximation of the actual values. Recognizing the potential errors in the calculated values, they nonetheless had to be used for the required calculations of mass discharge and the trajectory of an ice layer through the glacier.

Discussion of Results

In general, basal sliding accounts for 73 per cent of the observed surface velocities. The average shear stress at the bottom was 1.12 bars. These values are in agreement with other estimates of basal sliding for temperate glaciers. The marked decrease in sliding velocity at the center of the glacier across line 8 may be the result of increased bottom friction due to a large bottom load. This decrease occurs beneath a large medial moraine on the surface. Other seemingly unreasonable changes in englacial and bottom velocity may be the result of an incorrect estimate of the surface slope. However, on the whole, the velocities seem reasonable.

Discharge Relations

From these englacial velocities, the through-flow across fixed cross sections can be calculated and, by combining this with the ablation studies, one can determine the mass budget of a given section of glacier fairly accurately (see Fig. 22). This technique has been applied to two sections of Casement Glacier; one section is near the terminus between lines 2 and 3 and the other section is bounded by line 8 on the downglacier side and lines 9, 11, 12, and 13 on the upglacier side. For each section, the discharge through the lower cross sections and the inflow through the upper cross sections has been determined by graphical integration of the velocity profiles. If the sections were in equilibrium, the mass of ice moving into the section should be equal to the discharge plus the ablation.

Mass Budget of the Lower Glacier Section

The discharge through line 2 in 1965-1966 is estimated to have been 31.5×10^9 kg. The inflow into the section is estimated to have been 41.6×10^9 kg. The ablation over the area between the two lines was 18.5×10^9 kg. Combining these figures, a net budget for this section of the glacier may be determined and was -8.4×10^9 kg for the year 1965-1966. This loss would have resulted in a lowering of the surface by

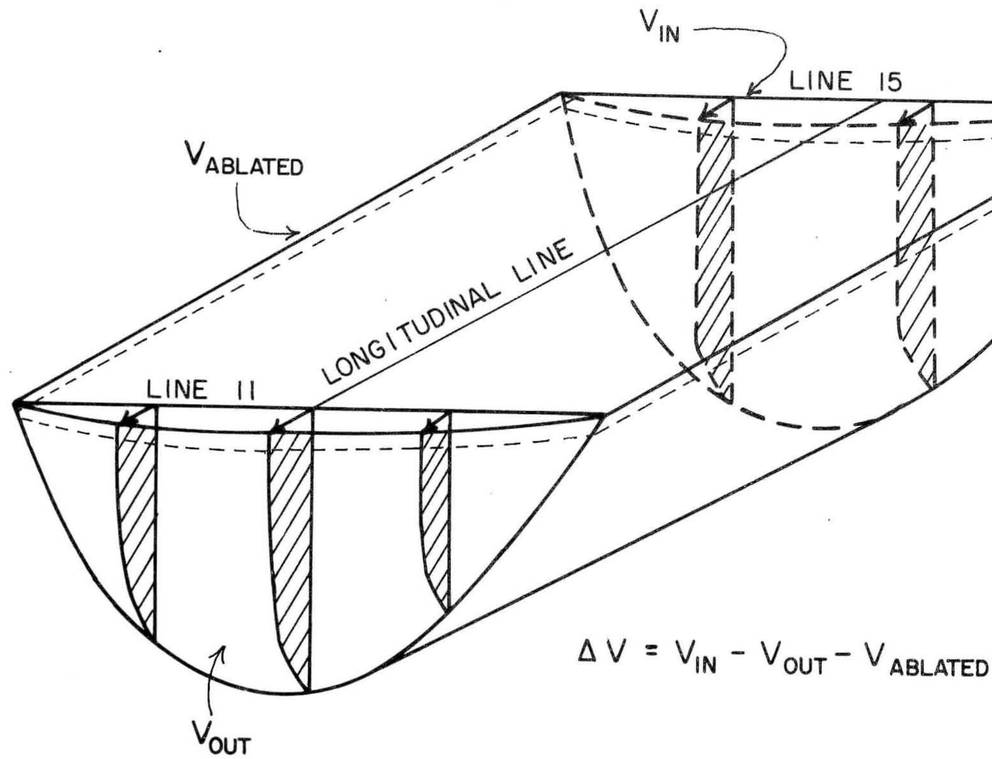


Fig. 22 - Diagram of proposed study of mass balance of a segment of Casement Glacier in which the net ice gain or loss could be measured by determining the inflow, the outflow, and the surface ablation.

approximately 2.8 m, a value which agrees fairly well with the value obtained from the surface lowering determined in the survey which for this section of the glacier averaged 2.3 m.

Mass Budget of the Upper Glacier Section

The discharge from this section is estimated to have been 79.0×10^9 kg/yr. The measured inflow was 99.5×10^9 kg, but this figure does not include any inflow from the tributary above the tunnel, between cairns 12 and 13. This ice stream is about one-half the size of the tributary between cairns 4 and 6 for which the inflow was 15.7×10^9 kg. Taking the inflow of the unmeasured tributary to be half of this value, 7.8×10^9 kg, a generous estimate, the net budget of this section of the glacier was -9.1×10^9 kg. This loss distributed over the 31 km^2 area of this portion of the glacier would have produced a lowering of the surface by 0.3 m. This value is also in rough agreement with the value derived from the changes in surface elevation over this section which averaged 0.9 m.

TABLE 7

SUMMARY OF MASS BUDGET DATA FOR LOWER AND UPPER SECTIONS OF CASEMENT GLACIER

Section	Inflow ($kg \times 10^9$)	Discharge ($kg \times 10^9$)	Ablation ($kg \times 10^9$)	Net budget ($kg \times 10^9$)
Lower	41.6	31.5	18.5	-8.4
Upper	107.3	79.0	37.4	-9.1

Trajectory of a Particle through the Glacier

The trajectory of a particle through the glacier has been calculated using the vertical component of the surface velocity and the englacial velocities. Figure 23 shows a longitudinal profile of Casement Glacier with the trajectory of points along the centerline drawn in. From this it is possible to estimate the travel-time of a given layer of ice, as it passes through the glacier.

Travel-time through the Glacier

The travel-time for a particle through the glacier from line 14 to line 2 has been calculated, using the surface velocities along the centerline of the glacier rather than the englacial velocities. This would result in a minimum value for the travel-time as the englacial velocities are lower than the surface velocities. Using this method a travel-time of 140 years was determined. The travel-time from points high up in the accumulation basins of each of the tributaries could easily approach 200 years.

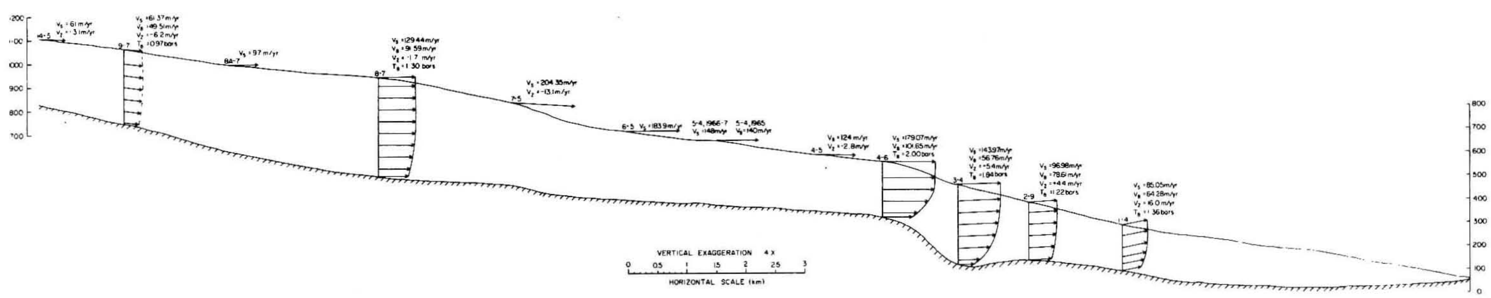


Fig. 23 - Longitudinal profile along centerline showing variation in ice thickness, horizontal surface velocity, the vertical components of velocity, and englacial velocity. Vertical scale in meters.

CHAPTER VII

ICE TUNNEL STUDIES

Introduction

Basal sliding has been recognized since the late eighteenth century as one of the important mechanisms in the movement of temperate glaciers (Lliboutry, 1964). A number of studies have shown that there are annual, seasonal, diurnal, and even short-term (on the order of minutes) variations in the surface velocities of temperate glaciers. These variations reach a maximum when considered on a seasonal basis in that the measured winter velocity may be 20-50 per cent lower than the mean annual velocity, and the summer velocity may exceed the average by 20-80 per cent, a situation which Elliston (1963) describes for Gorner Glacier. These observations led to the suggestion that the variations in surface velocity are the result of changes in the basal sliding rate (see list of references in section of this report discussing the variations in velocity).

However, due to the inherent difficulty in studying this type of movement, most ideas have been speculative. During the past two decades, the interest in the mechanics of basal sliding has resulted in the publication of numerous theoretical papers, principally by Weertman and Lliboutry, but only a few direct observations have been made.

Theory of Basal Sliding

Weertman's Theory

Weertman (1957) suggested that two mechanisms, pressure melting and plastic flow due to stress concentration, are responsible for basal sliding. Sliding of the glacier results when ice is melted by pressure melting on the upglacier side of an obstacle which is a zone of stress concentration. The meltwater flows around the obstacle and refreezes on the low-pressure side. The rate of melting and refreezing and the resulting ice movement depends on the rate of heat conduction through the obstacle. This rate increases with decreasing obstacle size and the resulting glacier movement is faster for small obstacles. The second mechanism proposed by Weertman is the enhancement of creep rate or plastic flow by stress concentration in front of obstacles. As the size of obstacles at the base of a glacier increases, the stress concentration also increases, enhancing the creep rate. The existence of both of these mechanisms was first verified by the field observations of Kamb and LaChapelle (1964) at the base of an ice tunnel in the Blue Glacier, Olympic National Park, Washington.

In order to formulate a theory of basal sliding, Weertman (1957) originally considered the movement of ice on a bed with regularly-spaced cube-shaped obstacles, with side length L, separated by distance L'. Assuming that the ice-bedrock interface can support no shear stress, τ, but that one exists in the ice, acting parallel to the bed, the average force on an obstacle is $\tau L'^2$ and the compressive stress, σ, on the upglacier face is $\tau L'^2/3L^2$. Weertman originally used the one-third factor to approximate the hydrostatic stress. In a subsequent refinement of his theory, Weertman (1964) considered irregularly-shaped obstacles whose dimensions were L_h, L_d, and L_p, the height and side lengths in the direction of and perpendicular to flow separated from each other by an RMS distance, L'. The more general expression for the compressive stress σ, becomes:

$$\sigma = \frac{\tau L'^2}{L_h L_p}$$

The factor one-third was eliminated on the basis of the limited experimental data of Kamb and LaChapelle (1964).

Basal Slip Due to Pressure Melting

The slip rate due to pressure melting or regelation can be determined from a knowledge of the difference in pressure on opposite sides of an obstacle of known size. The melting temperature of ice is pressure dependent, so that when the ice is at the pressure melting temperature, an increase in pressure will result in melting. The Clapeyron equation,

$$\frac{\partial T_m}{\partial p} = \frac{T_m(V_2-V_1)}{H}$$

relates the melting point temperature T_m, in degrees Kelvin, and pressure P, where V_1 and V_2 are the specific volumes $(1/\rho)$ for the liquid and solid phases, and H is the molal enthalpy of the phase transition (79.7 cal/g for ice). A one atmosphere increase in pressure lowers the melting point by 7.7×10^{-3} °C (7.6×10^{-9} °C/dyne cm^2).

If the average shear stress acting parallel to the bed is τ, the distance of separation of the obstacles L', and the obstacle dimensions, L_h, L_p, and L_d, then the average compressive stress, σ, on the glacier face given before will result in a lowering of the melting temperature by the amount

$$\Delta T_m = C \Delta P$$

where

ΔT_m = decrease in melting temperature of the ice

C = constant, 7.6×10^{-9} °C/dyne cm^2

ΔP = change in compressive stress given by $\tau L'^2/L_h L_p$

This produces melting on the upglacier face of the obstacles. The water flows around the obstacle to the low-pressure zone behind it and refreezes, liberating heat. This heat energy is then conducted through the obstacle at a rate determined by the temperature gradient through the obstacle, $C\Delta PL_d$, and the coefficient of thermal conductivity of the rock, D. Thus the amount of ice that can be melted in a unit of time, assuming that all of the heat is transmitted through the block, may be expressed as:

$$\text{Volume} = \left(\frac{C\tau L'^2}{L_h L_p L_d}\right) \times \frac{L_h L_p D}{H_\rho} = \frac{C\tau L'^2 D}{L_d H_\rho}$$

The "sliding velocity" due to pressure melting may then be determined by dividing the volume of ice melted by the cross-sectional area of the obstacle, giving $S_{pm} = C\tau L'^2 D / L_p L_d L_h H_\rho$. This equation may be rewritten, letting L be the average dimension of the obstacle ($L^3 = L_h L_p L_d$) and including a factor to take into account the heat flow that might be conducted through the surrounding ice or the water film around the obstacle, α:

$$S_{pm} = \alpha \frac{C\tau L'^2 D}{L^3 H}$$

If the heat flow is confined to the obstacle, $\alpha = 1$, and if not $\alpha > 1$. Hence the slip rate due to pressure melting is inversely proportional to the obstacle size.

Basal Slip Due to Plastic Flow

The creep rate or strain rate of ice, $\dot{\epsilon}$, given by Glen's creep law (1955) is:

$$\dot{\epsilon} = B\sigma^n$$

where σ is the stress, n is a constant equal to 3 or 4, and B is another constant equal to 0.017 $\text{bar}^{-n}/\text{yr}$ when the stress is uniaxial, whether tensile or compressive. Although the value of B is temperature dependent, calculations show that for the small range of temperatures at the bottom of a temperate glacier the value of B is affected very little.

It has already been shown that $\sigma = \tau L'^2 / L_h L_p$, so that Glen's equation may be rewritten as:

$$\dot{\epsilon} = B(\tau L'^2 / \beta L_h L_p)^n$$

where $\beta = 1$ if the hydrostatic pressure is not sufficient to prevent the formation of a cavity behind the obstacle and $\beta = 2$ if it is. The velocity due to stress concentration is then equal to the creep rate times the distance over which it is effective (assumed to be equal to the size of the obstacle).

$$S_{pf} = \dot{\epsilon} L_d = B(\tau L'^2/L_h L_p)^n L_d$$

Thus, it can be seen that the larger the obstacle, the larger will be the velocity due to plastic flow.

Sliding Velocity

In his original paper, Weertman (1957) considered that the sliding velocity of a glacier whose bed contains a full spectrum of obstacle sizes is determined by those obstacles for which $S_{pm} = S_{pf}$, and that only the controlling-sized obstacles hinder the flow. This assumption is obviously an over-simplification as the smaller and larger obstacles also influence the slip rate.

In light of this criticism, Weertman (1964) refined his theory by considering the effect of obstacles, both smaller and larger than this controlling size on the sliding velocity.

The bed of a glacier is made up of a complete size range of obstacles, but for convenience of calculation, Weertman considered only those sizes whose average dimensions are one order of magnitude larger than the preceding size (λ is the average dimension of the smallest, 10λ the next size larger, 100λ next, ..., the largest size being 1/10 the thickness of the glacier).

The shear stress, τ, transmits a total force of τA over the bed of the glacier of area A. Each size group of obstacles will transmit some portion of the total force. The obstacles of the critical size range will transmit the largest portion of the force. If the force transmitted by obstacles of the size $10^i\lambda$ is given as $\tau_i A$, then

$$\sum_{i=0} \tau_i A = \tau A$$

where τ_i is regarded as the effective shear stress which causes flow of ice around obstacles of size $10^i\lambda$. Since the sliding velocity must be the same for every size of obstacle, it follows that

$$S = (S_{pm} + S_{pf})_i = (\alpha C \tau_i D/H_\rho L_i)(L_i'^2/L_i^2) + bBL_{d_i}(\tau_i L_{d_i}/\beta_i L_i)^n (L_i'^2/L_i^2)^n$$

where S is the actual sliding velocity and the subscripts give the values of the various parameters for that particular size of obstacle.

Making some approximations, Weertman solved the above equation for τ_i in terms of S and substituted the values into the summation, $\sum_{i=0} \tau_i = \tau$. This reduces to $\tau = 2.314\ \tau_\lambda$, where τ is the total applied shear stress and τ_λ is the effective shear stress acting on the controlling obstacles when the value of β is equal for all terms (cavities can form behind obstacles). The term becomes $\tau = 3.405\ \tau_\lambda$ when $\beta = 1$ for the controlling obstacle size, but is equal to 2 for larger obstacles. For these two limiting cases, it can be seen that the effective shear stress on the controlling-sized obstacles is only one-half to one-third of the applied shear stress.

An expression for determining λ, the controlling obstacle size, is derived by setting $S_{pm} = S_{pf}$ and solving for λ. This gives the equation:

$$\lambda = (\alpha CDK^{n-1}\ \beta_\lambda{}^n / H_\rho b B_r{}^{2n-2} \gamma^{n-i} \tau^{n-i})^{1/2}$$

This equation is substituted into another equation which allows the calculation of the sliding velocity as a function of the shear stress on the bed

$$S = 2S_{pm} = 2(\alpha CDbB\gamma^{n-1}/H_\rho \beta_\lambda{}^n)^{1/2}(\tau r^2/k)^{(n+1)/2}$$

where, by setting $\alpha = 1$, $b = 1$, $\gamma = L_{di}/L_i = 1$, $n = 3$, $C = 7.4 \times 10^{-3}$ °C/bar, $B = 0.017\ \text{bar}^{-n}/\text{yr}$, $D = 0.005\ \text{cal}/°\text{C-sec cm}$, and assigning values to τ, β, k, and r as conditions dictate, the theoretical value of sliding velocity can be determined. Alternatively, knowing the value of S and τ, one can calculate the value of $r(L'/L)$, the roughness parameter, or λ, the controlling size.

Lliboutry's Theory

Lliboutry (1959) argued that the substitution of realistic values for some of the constants in Weertman's equations resulted in sliding velocities that were too low. He reasoned that this was a result of the unrealistic bed model that Weertman used for his calculations. Lliboutry developed his own theory of sliding centered around a bed form consisting of a series of obstacles shaped like sine waves (commonly referred to as the "washboard" model) with amplitude a and wavelength λ. Employing the same processes of sliding as Weertman, but using his modified bed model, Lliboutry derived an equation which gives the expected sliding velocity:

$$S = S_{pm} + S_{pf} = \frac{Ba}{2r^2}\left[\frac{2\tau_b}{\sqrt{3}\pi r}\right]^n$$

Taking B = 0.18 bar-yr$^{(-1/h)}$, n = 3, and r = 0.1 (a/λ), Lliboutry found a sliding velocity of 4 m/yr, which he considered to be too low. Therefore, he suggested that the glacier might not be in intimate contact with the entire bed, but rather, that the ice rests only on the crests of the ridges and that the cavities beneath the glacier are filled with water under pressure which would be capable of supporting at least part of the mass of the glacier. With this modification, the new equation of the sliding velocity becomes:

$$S = \frac{BZ}{2\tau b^2}\left(\frac{Z}{\sqrt{3}\tau_b\lambda}\right)^n$$

where $z = a\pi^2(\rho gh-p)$, p = the hydrostatic pressure.

Lliboutry (1968) has recently modified his bed model to include the effect of a range of sinusoidally-shaped ridges with several different wavelengths and amplitudes, superimposed on one another.

Comparison of the Two Theories

Both of the theories appeal to pressure melting and plastic flow as the important mechanisms in the sliding process. The main differences between the two theories are the shape of the bed model and the existence and effect of water under pressure at the bottom of the glacier.

Weertman (1967) criticizes Lliboutry's bed model pointing out that a glacier bed that is rough in only one direction is not realistic. The point may be made also that Weertman's bed of blocks is not realistic either. The Lliboutry model's strength is that it most nearly approximates the longitudinal variation in obstacle shape and size, but the assmuption of wide lateral extension of these bumps is the model's shortcoming. The problem is that there is not much known about the roughness of a glacier bed and until that time when more is known about the configuration of the beds of glaciers, the controversy cannot be resolved.

Weertman (1967) also questions the existence of a layer of water under pressure as Lliboutry has suggested. In Weertman's theory the water pressure at the bottom is the overburden pressure, and water is free to flow along the bed.

Experimental Results

Kamb and LaChapelle (1964) conducted laboratory experiments in which they pulled 1-cm cubes of rocks and other materials through blocks of ice. If one assumes that the flow of heat through the cube is one-dimensional because the thermal conductivity of the cube is large compared with that of ice, then the velocity of the cube through the ice can be calculated. Kamb and LaChapelle used the following equation to calculate the velocity:

$$V = \frac{KC\sigma}{H\rho L}$$

where K is the thermal conductivity of the cube material, C is the slope of the pressure-melting point curve 7.6×10^{-9} °C/dyne-cm^2, $H\rho$ is the heat of ice fusion per unit volume, L is the cube edge length and σ the compressive stress on the loaded face.

The agreement of the observed flow rates with the theoretical values is not good. Kamb and LaChapelle account for the disagreement by considering the loss of meltwater by leakage along the constantan wire. Eash gram of water that was lost removed 80 calories from the regelation cycle and so they state that the regelation process was controlled by the conductivity of the ice rather than by that of the cube. Why this is so is not readily apparent to the writer.

Drake (1965) conducted experiments on regelation by pulling wire loops through blocks of ice. He found that the velocity of the wire through bubbly ice was significantly lower than through bubble-free ice and suggested that the reason for this behavior was that the water produced in the pressure-melting process drained into the holes in the bubbly ice, depriving the regelation system of energy (pressure melting, refreezing and release of 80 cal/g, conduction of heat to the face where the pressure-melting is occurring). Thus the water layer around the wire played an important role in determining the velocity of the wire through the ice. Drake also found that the velocity of the wire through the ice was not significantly altered by changes in thermal conductivity of up to four orders of magnitude. Weertman has suggested that S_{pm} is directly proportional to the thermal conductivity of the obstacle, but Drake's results indicate that the conductivity is not important in determining the pressure melting component of the sliding velocity.

Field Results

The most important field studies so far reported have been those of Kamb and LaChapelle (1964) and Theakstone (1967). Kamb and LaChapelle made the following observations in a tunnel into Blue Glacier, Washington: (1) 90 per cent of the observed surface velocity of 1.8 cm/day resulted from basal slip; (2) the measured basal slip rate showed marked irregularities over intervals of the order of seconds, and diurnal variations in slip rate of up to 10 per cent; (3) a layer of regelation ice (0-2.9 cm thick), which was both structurally and texturally distinct from the ice above it, was observed at the bottom of the glacier; (4) the basal ice froze to the bedrock when the overburden pressure was released verifying the existence of pressure melting; (5) the regelation layer had a higher debris content than the normal glacier ice above it; and (6) at points of separation of the ice from the bedrock, needle-like regelation spicules formed.

In 1961 and 1962 Theakstone made measurements of the surface velocities and the rate of basal sliding in natural cavities beneath the glacier Østerdalsisen, Norway. At this location along the margin of the glacier, basal slip accounted for 60-90 per cent of the observed surface movement. From 1961 to 1962 the observed summer surface velocity 50 m from the margin decreased from 8.4 cm/day to 7.6 cm/day; the mean basal slip rates for the summer also decreased, from 5.6 in 1961 to 4.8 cm/day in 1962. The mean slip rate for the 1961-1962 winter was 2.9 cm/day, lower than the summer values. Theakstone also reports an increase in slip rate during periods with heavy precipitation. Jerky, irregular motion observed in the bottom few centimeters, but not recorded a few centimeters above the floor, was explained by Theakstone as the result of "stick and slip" motion of the basal ice. However, Theakstone suggests that this jerkiness is a local feature produced by the jamming of the basal ice against the bedrock on the down-glacier side of the cavity and may not be typical of the type of movement at the center of a glacier.

Casement Glacier Studies

Objectives

The tunnel observation program was designed to provide basic data about the manner and mechanics of basal sliding at the ice-bedrock contact exposed in a hand-excavated tunnel. Specific objectives were: (1) to determine whether basal sliding is continuous or intermittent, (2) to determine if there is any diurnal variation in slip rate and any difference between slip rates on sunny and cloudy days, and (3) to observe the mode of flow of ice around artificial obstacles placed on one of the exposed bedrock knobs.

Selection of the Tunnel Site

The location for the tunnel was chosen carefully, paying close attention to the sharpness of the ice-bedrock contact and avoiding nearby meltwater streams which flow into the tunnel. It was considered of greatest importance to find a site at which the ice was sliding over bedrock and where the surface velocity was high. Such a location was found in early July, 1966 and tunnelling began immediately. The chosen location was about 3.5 km west of the upper basecamp (Fig. 3).

Excavation of Tunnel

In 1966 the tunnel was excavated into the front of a small icefall (Fig. 24). The drift was approximately parallel to the direction of ice flow. After digging the first 10 m, a large cavity beneath the glacier was broken into. This cavity, a series of interconnected grooves in the bottom of the glacier, was formed as the ice flowed over large bedrock knobs. As the ice was flowing rapidly (2.9 cm/day) relative to the closure rate due to the overburden pressure (0.5-2.0 bars, due to 5-20 m of

Fig. 24 - Entrance to 1966-1967 ice tunnel in upper Casement Glacier, showing position along ice-bedrock contact. The tunnel was excavated parallel to ice flow direction.

ice), the grooves and flutings which were produced in the sole of the glacier as the ice slid over the bedrock knobs remained open for some distance downglacier. In some places these grooves could be followed for 25 m before the grooved ice came in contact with bedrock (Figs. 25 and 26).

A second drift was dug at the head of one of the largest grooves exposing two bedrock knobs. As the downward slope of the upglacier side of the knobs was 30°, the tunnel was extended horizontally rather than along the bedrock surface, because a drift following the bedrock contact would have filled with water. After tunnelling an additional 18 m, work in this drift was halted in order to concentrate the sliding studies on the bedrock knobs that were already exposed (see map of cavity and tunnel, Fig. 27). In July 1967 the same cavity was re-excavated and additional observations made on the mechanics of basal sliding.

Measurement of Slip Rate

Method of Measurement

At the exposed ice-bedrock contacts (Fig. 28), 1.27-cm wooden dowels were placed in holes drilled in the ice at 25-cm intervals above the bed to a height of 150 cm. An additional dowel was placed at 10 cm above the ice-bedrock contact. Reference marks were made in the bedrock for determining relative ice velocities and absolute slip rates by measuring the displacement from a plumb bob suspended from the top dowel.

In 1967, two Starrett dial-gauge micrometers were used to measure accurately short-term variations in slip rate. These instruments are calibrated to 0.001 inch and readings can be estimated to the nearest 0.0002 inch. Gauge I was mounted on a wooden stand which could be moved along a 5-cm x 5-cm wooden beam securely fastened to the bedrock knob (Fig. 29). The piston, which is connected to the rack operating the gauge, was kept in contact with a 1.27-cm dowel placed in the ice 20 cm above the ice-bedrock contact (it could not be positioned any lower because of the debris layer at the bottom of the glacier). Gauge II (Fig. 30) was fastened directly onto a rock bolt with its piston in contact with a small piece of wood nailed to the end of a dowel that had been drilled into the ice 20 cm above the bedrock. The locations of the two gauges are shown in Figure 27.

Results from Measurements of Slip Rate

Seasonal and annual slip rates

Between 5 and 28 August 1966 all dowels from 10 to 150 cm moved at an average rate of 2.9 cm/day. In July 1967 the movement of the dowels since August 1966 was measured. During the time elapsed since the last measurement, the mean slip rate was 2.3 cm/day, 20 per cent lower than

Fig. 25 - View of glacier cave showing part of large groove that was produced in the ice at the bottom of Casement Glacier where it flowed over the bedrock knob seen in the background. The material in the left foreground is bedrock with a thin veneer of debris. The width of view is about 2.5 m. The flow is toward the viewer.

Fig. 26 - Photo of groove at the head of which the second drift of the tunnel was excavated exposing the bedrock knobs for the movement studies. The width of the field of view is 3 m.

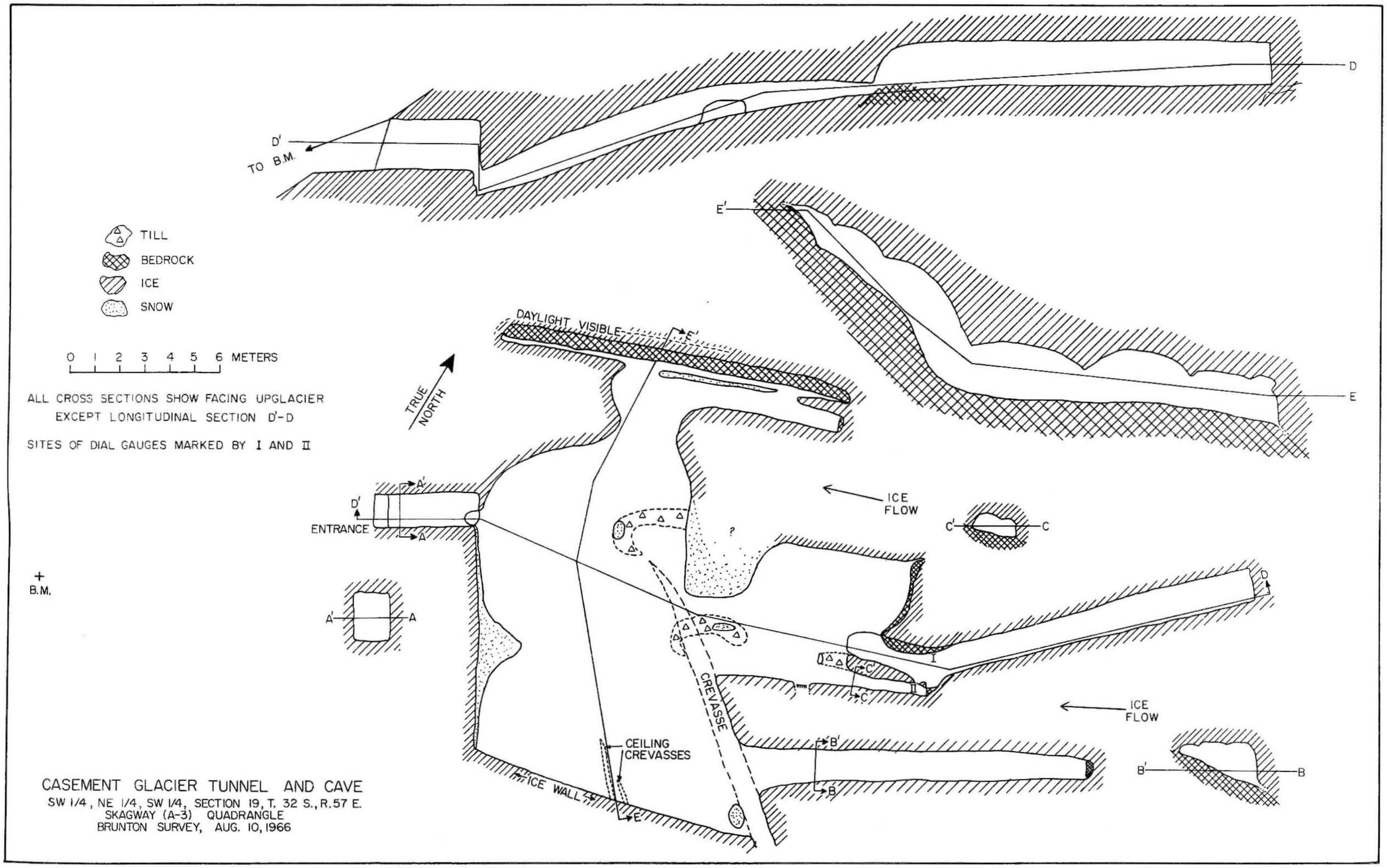


Fig. 27 - Map and cross-sections of the Casement Glacier tunnel and cave. The locations of the gauges used to measure the slip rate are indicated on the map.

Fig. 28 - View of wall of tunnel looking downglacier. The dowels were used to measure seasonal slip rate.

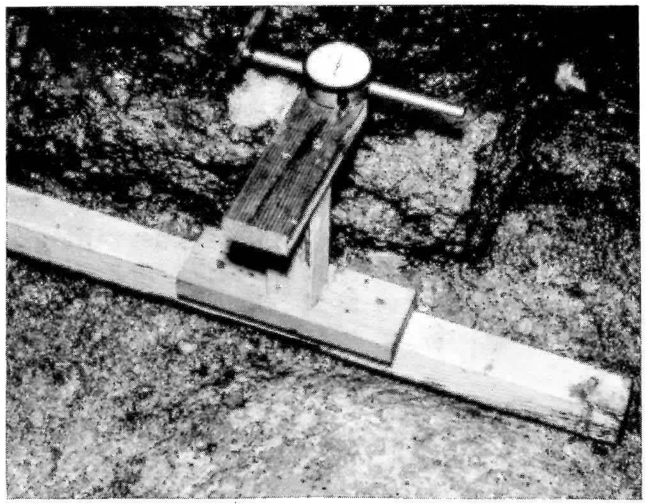


Fig. 29 - Photo of Gauge I. The instrument is fastened to a stand which can be moved along a wooden beam bolted to the bedrock. The piston of the gauge is placed against a dowel that is in the ice. The ice flow is from right to left.

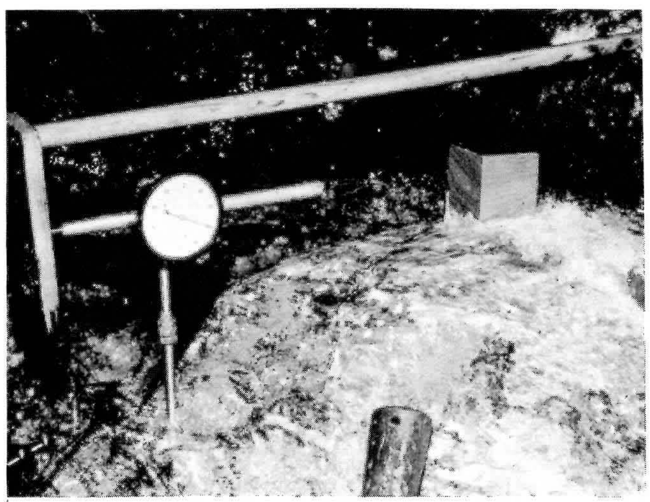


Fig. 30 - Photo of Gauge II. This instrument is fastened to bedrock by rockbolts. The numbers on the dial are 0.01 inch and the marked intervals are 0.001 inch. The dowel is drilled 0.5 m into the ice parallel to the flow vector which is right to left. Note the polished surface on the bedrock knob and the plucked, more steeply dipping portion into which the rock bolt is drilled. The cubes on the bedrock are 5.0 and 2.5 cm on a side.

the measured summer rate for 1966. At the same location in August 1967 the mean slip rate was 2.6 cm/day, 10 per cent less than in 1966.

The observed decrease in mean slip rate from the end of August 1966 to the end of July 1967 does not reveal the true magnitude of the decrease of slip rate during the coldest part of the winter, when the quantity of lubricating free water would have been a minimum. It is certainly possible that the minimum slip rate during the winter was less than one-half of the maximum summer slip rate.

At surface velocity marker 8-13, located about 100 m from the entrance of the tunnel, the mean winter velocity was 14 per cent lower than the 1966 summer velocity. In fact there was a measurable decrease in surface velocity during the winter observed at almost all of the movement stakes (see seasonal variations in velocity, Chapter II). The per cent decrease is a maximum at the sides of the glacier and a minimum at the center where the thickness of the ice is greatest. This suggests that as ice thickness increases from the side to the center of the glacier, the role of basal slip becomes less important and englacial shearing becomes more important.

Short-term variations in slip rate

Field observations (Washburn and Goldthwait, 1937; Millescamp, 1956a and 1956b; Klebelsberg, 1948; Meier, 1960) indicate that glaciers flow in a series of discrete movements with periods of stress build-up (either tensile or compressive) preceding each jump. Lliboutry (1965 and 1968) and Goldthwait (personal communication) infer that this discontinuous movement should also exist at the ice-bedrock interface. On the other hand, McCall (1952) has found that during two 12-hour studies of ice-bedrock slip, the movement was continuous.

To investigate this problem, on 7 August 1967 the two dial strain gauges were read every minute for a 1.5-hour period. Plots of the readings from the two gauges against time indicate that the rate of slip is linear (Fig. 31). A more definitive way to test the linearity of a set of data is to plot the deviations from a best-fit straight line. Figure 32 is a plot of the deviations from the computed best-fit line. The curves are basically the same shape, but the deviations at Gauge I rarely exceeded 0.0003 inch, the reading accuracy of the instrument. Even if the departures from the best-fit line are real, they represent only small short-term variations in slip rate and do not suggest stick-slip motion. The slip rate at Gauge I during this interval was 2.34 cm/day and at Gauge II was 2.98 cm/day. The higher slip rate at the site of Gauge II is not fully explained, but may result, in part, from plastic closure of the side drift in which the instrument was located. The important observation is that at no time during the 1.5-hour period was any discontinuous movement noted. Similarly, during the 24-hour study (see below), although observations were not made as continuously as during the 1.5-hour study, no jump of the needle on the dial gauge was

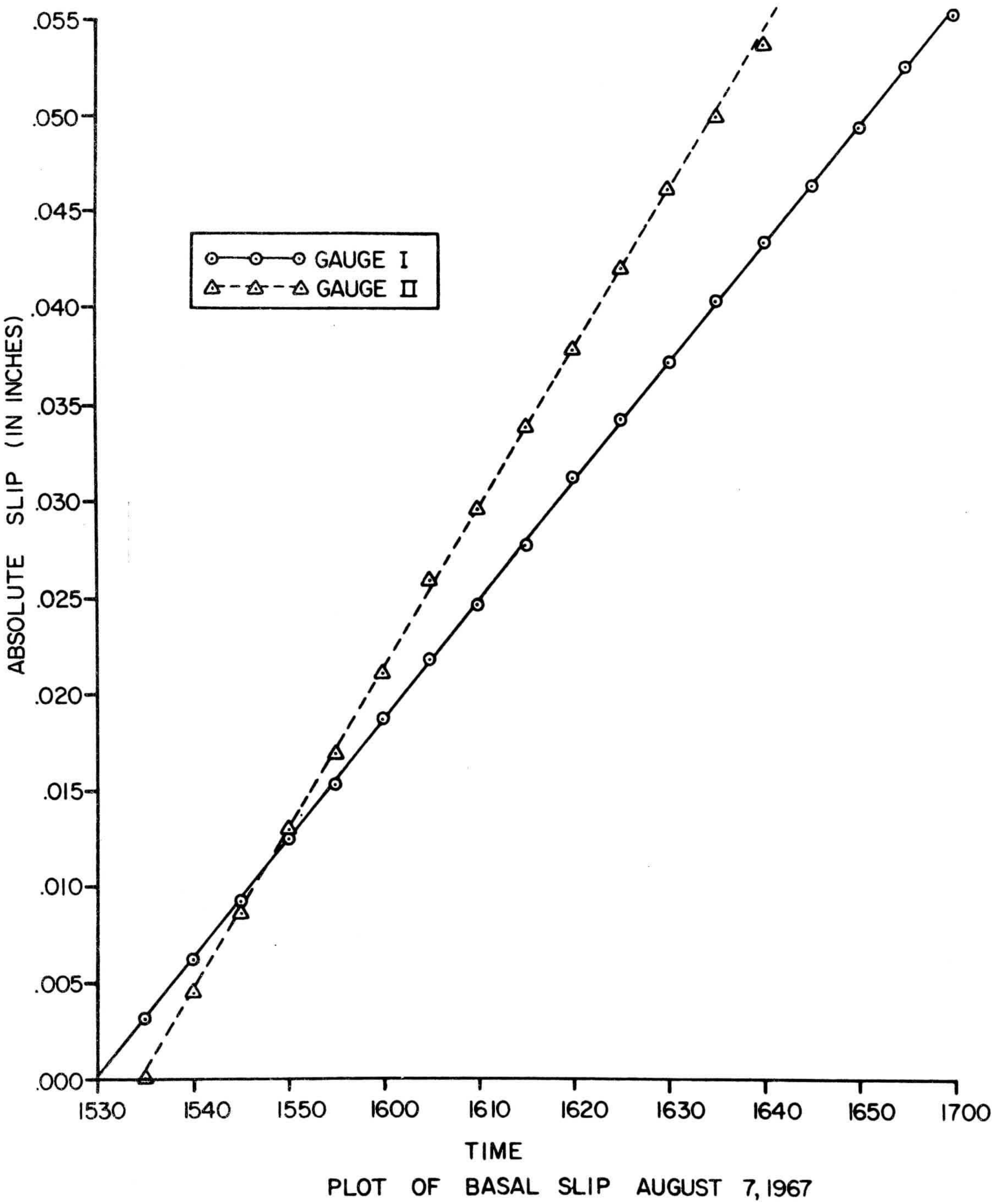


Fig. 31 - Plot of movement observed at Gauges I and II in the 1-1/2 hour study.

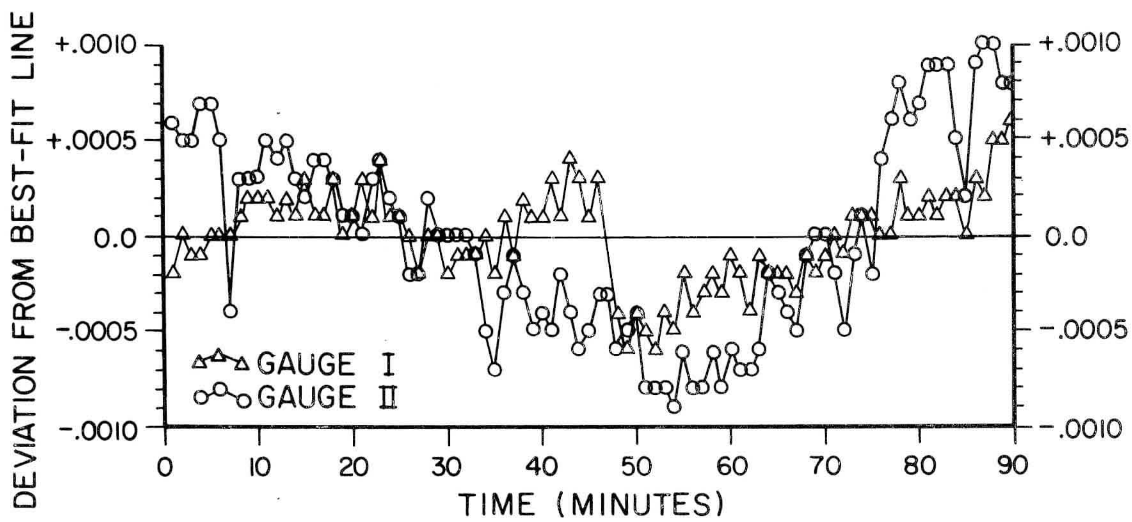


Fig. 32 - Plot of departures from the best-fit straight line. The lines are the best-fit straight lines for each set of data.

observed. In the only study (Theakstone, 1967) in which irregular motion near the bottom has been recorded, the jerkiness was observed in only the bottom few centimeters and the motion was continuous just a few centimeters above the bed (the exact distance is not specified). Since the dowels in the ice were 20 cm above the bedrock, it is possible that there was stick-and-slip movement along the bottom, but it seems unlikely. It is possible that Theakstone's observations were produced by a local situation and that it should not be considered as representative of the conditions at the center of a glacier. The problem cannot be satisfactorily resolved until many more observations on the characteristics of the slip process have been made.

McSaveney and Gage (1968) have reported diurnal variations in the surface velocity of the Franz Josef Glacier. To determine whether there is a diurnal variation in slip rate that might be related to the availability of lubricating basal meltwater, it was proposed to spend 48 hours in the tunnel during a period with no rain so that the quantity of water at the ice bedrock interface could be estimated from the ablation data. In this way a clear-cut relationship could be established between the quantity of water and the changes in sliding velocity. However, extended periods of bad weather during August forced alteration of these plans, and the tunnel observations were made when weather conditons on the surface prevented surveying. The basal slip was measured in two periods, one of 24 hours and the second of 48 hours duration. During the 24-hour study the gauges were read every five minutes. When the study started at 1300 hours on 10 August 1967, a light rain was falling which slackened rather abruptly to a heavy mist at about 0000 hours on 11 August. During the 48-hour study, the gauges were read every 0.5 hour. Detailed precipitation records were not kept during this period other than the standard meteorology observation times at the base camp. The precipitation data and the corresponding time intervals are shown together with the movement data for the 48-hour study in Figure 33.

The readings from the 24-hour study show a definite decrease in slip rate (Fig. 34) about two hours after the slackening of precipitation on the surface. The observed decrease in slip rate probably resulted from a decrease in water available for bottom lubrication which would produce a thinning of the basal water layer and a subsequent increase in the contribution of obstacles smaller than the controlling size. The plot of the readings from the 48-hour study (Fig. 33) shows irregular slopes which are related to the intermittent nature of the precipitation during that period. One aspect of the observations which cannot be explained satisfactorily is the seemingly contradictory changes in slope at the two gauges during the 48-hour study. The plots suggest breaks in slope at about the same times, but in the opposite sense.

Discussion

In the tunnel, both in 1966 and 1967, there was no differential slip measured in the bottom 1.5 m of ice. Kamb and LaChapelle (1964) observed

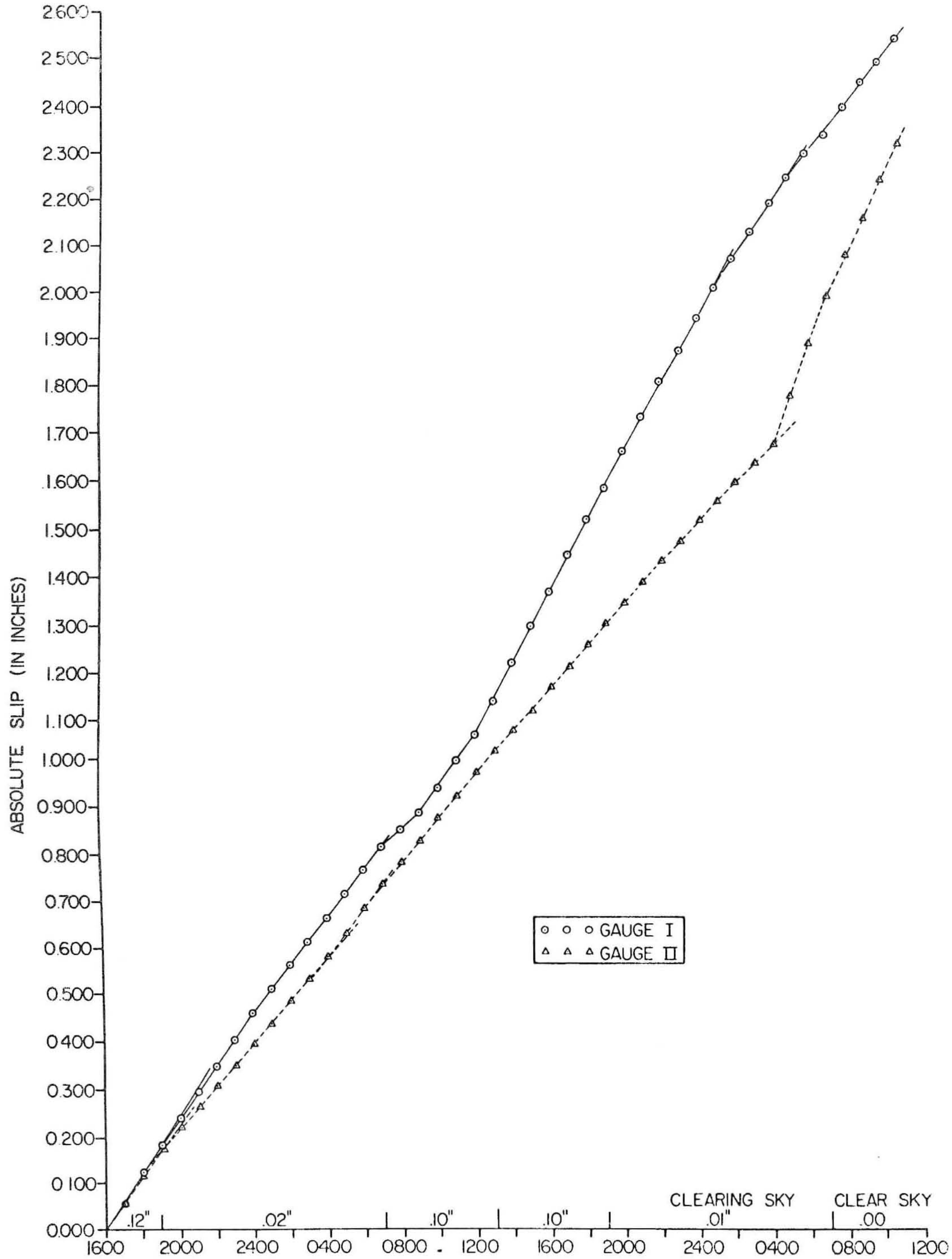


Fig. 33 - Plot of movement observed in the 48-hour study.

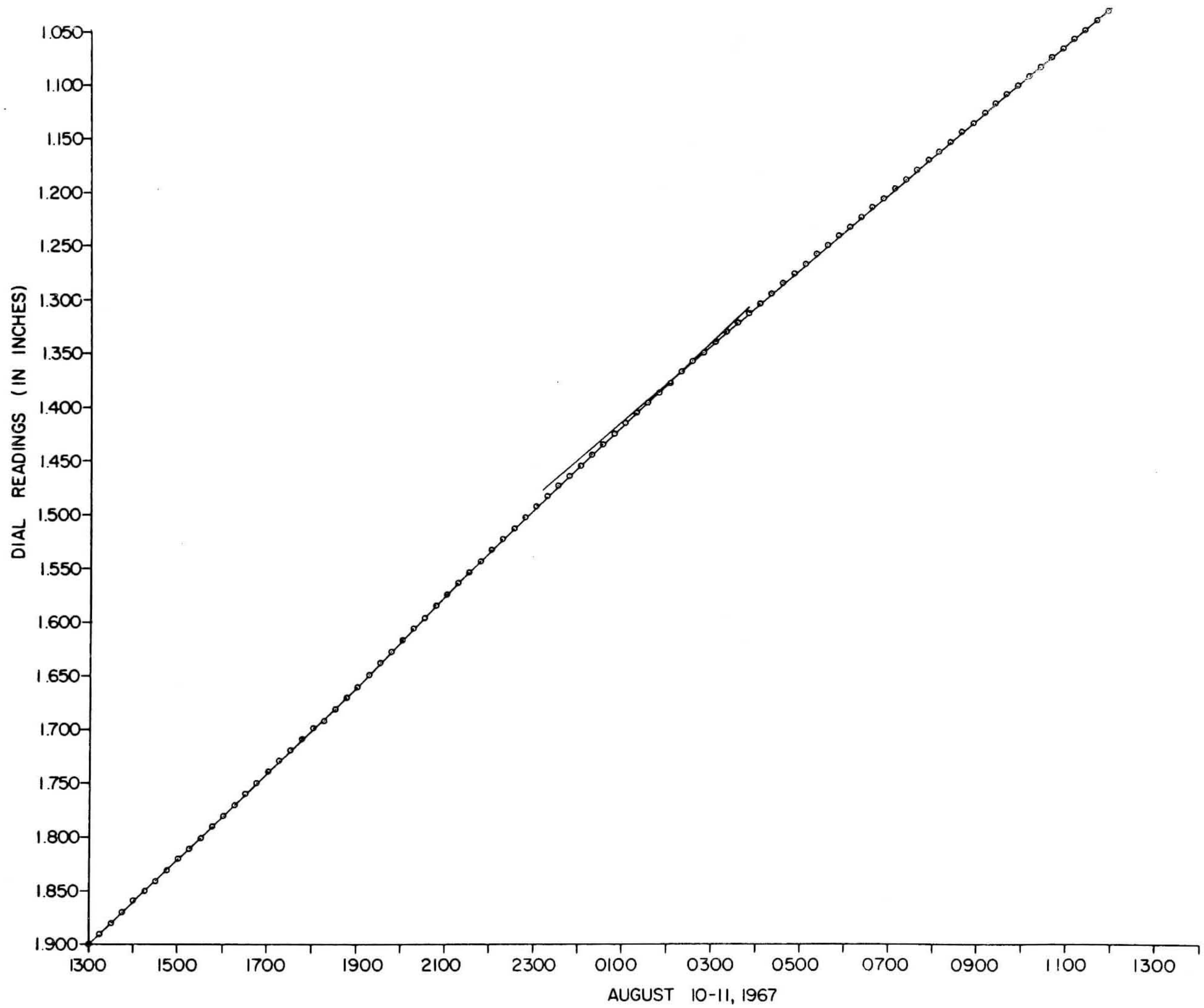


Fig. 34 - Plot of movement observed in the 24-hour study.

that a dowel at 1.5 m above the bedrock moved 12 per cent faster than one at 0.1 m. They determined that most of this difference occurred as uniformly distributed shear except for two irregularities in the bottom 0.5 m suggestive of discrete shear zones. The ice thickness at the point of their observations was 26 m, whereas, in the Casement Glacier tunnel, the ice was only 12 m thick at the point of observation.

The motion of a glacier takes place partly by sliding on its bed and partly by continuous distortion within the ice caused by stresses set up by the weight of the glacier. There are two stresses acting in opposition at the bottom of a glacier: frictional stress and shear stress. Shear stress acts to produce movement and frictional stress tends to retard it. In a classical model for friction, frictional force, f_k, is proportional to the thickness of the overlying layer of ice and may be found by the following equation:

$$f_k = \mu_k N = \mu_k \rho g h \cos \alpha$$

where μ_k is the coefficient of kinetic friction, N is the normal force on the surface, and α is the slope of the bed. The frictional force will be a minimum at the sides and a maximum at the center of a glacier, where the ice thickness is a maximum. The shear stress also increases with ice thickness. If ice could be regarded as a perfect plastic, the shear stress would reach a maximum value when the yield stress of the ice is reached. As, in fact, the strain rate of ice follows a power of the applied stress, at the sides of the glacier where frictional resistance to sliding is lowest, the shear stress may be sufficient to produce sliding on the bed but not much englacial deformation. Thus, a high percentage of the observed surface movement is a result of basal sliding. As the ice thickness increases, the frictional stress and the shear stress at the bed and within the glacier also increase. This may produce two results: (1) the rate of basal sliding will increase because of the increased shear stress and (2) the amount of englacial shearing will increase because the increased frictional stress will cause a higher proportion of the shear stress to be relieved by englacial deformation or shearing. One would expect, therefore, to find the magnitude of the basal sliding velocity to increase to the center of the glacier where it would attain a maximum value, but at the same time, the per cent of observed surface velocity due to basal sliding would decrease to a minimum at the center. This suggestion has not been tested quantitatively, but data indicate that it is valid.

At the tunnel the surface slope varied from 30° above the point of the observations to 45° at the entrance. Substituting these values into the equation for the calculation of the shear stress, and setting h = 12, a range of shear stress values from 0.50 to 0.75 bars is obtained. Using this range of shear stress values and the observed annual sliding velocity of 10 m/yr, the roughness ratio (L'/L_d) and the controlling obstacle size can be estimated after Weertman (1964, Fig. 3). The roughness factor of the bed ranges from 10-12 and the controlling obstacle size ranges from 0.8-1.0 cm. If the maximum thickness of the regelation layer can be used to approximate the controlling obstacle size, as has been suggested by Glen (1955), the theory and observations agree quite well, as the maximum observed thickness of the regelation layer was about 1.0 cm.

Weertman (1964) also gives an equation for the distance, X_o, that a cavity will remain open behind an obstacle of size λ:

$$X_o = \lambda(\tau r^2/k)^n/(\rho g h)^n$$

where k is a constant and has a value between 2.314 and 3.405. The equation was derived for conditions with constant ice thickness; however, it can be used to estimate the length of a cavity formed under conditions such as exist at the Casement Glacier tunnel. Substituting the Casement data into the equation, X_o is calculated to be 44 m for an obstacle 1 m high. The cavity behind one obstacle, the downglacier side of which was 1 m high, extended downglacier 25 m. If the height of the upglacier side of this obstacle was less, as is probable, say 0.5 m, then the calculated cavity length would be 22 m.

Effect of a Layer of Water on the Sliding Velocity

Weertman (1962) determined that a basal layer of water thicker than the height of the controlling obstacle would produce an increase in the sliding velocity. In a re-examination of the problem, he (1964) altered his original estimate and stated that a layer of water an order of magnitude thinner than the controlling obstacle size would produce an increase in the basal slip rate. Thus, depending upon local conditions (shear stress at the bed, controlling obstacle size, bed velocity), the commonly observed increase in velocity during the summer months could be produced by a basal water layer from 0.35 to 1.00 mm thick. The quantity of free water could also affect the rate of englacial shearing and deformation, but analysis of these changes would require data on the seasonal variation in the englacial velocity, which was not obtained because of the failure of the deep-drilling program.

The results of the Casement Glacier tunnel study verify the importance of basal lubrication in the movement of temperate glaciers. The basal slip measurements coupled with the surface velocity measurements substantiate the suggestion that the observed annual, seasonal, diurnal, and short-term variations in surface velocity are the result of changes in basal sliding rates, which, in turn, are a function of the thickness of the water layer at the bottom of the glacier. This layer has maximum thickness during the summer, resulting in the highest basal slip and surface velocities.

Emplacement of Artificial Obstacles on Bedrock

Introduction and Method of Emplacement

Weertman (1957, 1964) states that the size of an obstacle on the bedrock determines the dominant mode of flow of ice around it, plastic flow predominating for larger obstacles and pressure melting for obstacles smaller than a "critical size". Kamb and LaChapelle (1964) disagree, stating that from their results, the spacing of the obstacles, rather than their size is most important in determining the type of prevailing flow. In their theory the transition from regelation slip to plastic flow would occur when the "natural length" is 0.5 to 1.0 m. They seem content to leave the definition of "natural length" vague.

To test Weertman's ideas, two cubes each of 1- and 2.5-cm side lengths and one with 5-cm side lengths were fastened to one of the exposed bedrock knobs (Fig. 35). The placement of these cubes was exceedingly difficult as the tunnel walls were constantly melting and dripping onto the work area. This water made drilling the holes for the rock bolts, which were used to help hold the 5- and 2.5-cm cubes in position, very slow as the powdered rock formed a paste and clogged the bit. Each hole took an hour or more to drill. After two holes were drilled, the surface was dried with a propane torch and the two rock bolts were placed and cut to the proper length. Epoxy was smeared over the bedrock, the rock bolts, and the bottom of the cube, after which the cube was slipped onto the rock bolts and the whole area was kept warm and dry with the torch for several minutes, so that the epoxy could harden. Rock bolts could not be used to hold the 1-cm cubes because of their small size, so they were fastened only with epoxy.

Results

Because of its high debris content, the basal ice could not flow around the obstacles as debris-free ice would. As a result, only one 2.5-cm and one 1-cm cube remained intact and fastened to the bedrock after the ice came into contact with them. The 2.5-cm cube was placed with a horizontal diagonal upglacier (Fig. 36) to reduce the compressive stress on the upglacier side. The 1-cm cube had been completely covered with epoxy so that the epoxy formed a sloping front of about 45°.

The flow of the ice around the 2.5-cm cube produced a groove (Figs. 37 and 38) in the sole of the glacier. The cavity was 0.5 cm narrower than the diagonal width of the block and was lined with a layer of regelation ice, 2 mm thick (Fig. 39). Vertical closure was not measureable. Both regelation slip and plastic flow were operating in the movement of the ice around the cube.

The 1-cm cube also produced a groove lined with a layer of regelation ice about 2 mm thick, but this cavity exhibited no measureable closure over a distance of 21 cm (the distance the ice had moved past the cube before it had been sheared off the bedrock).

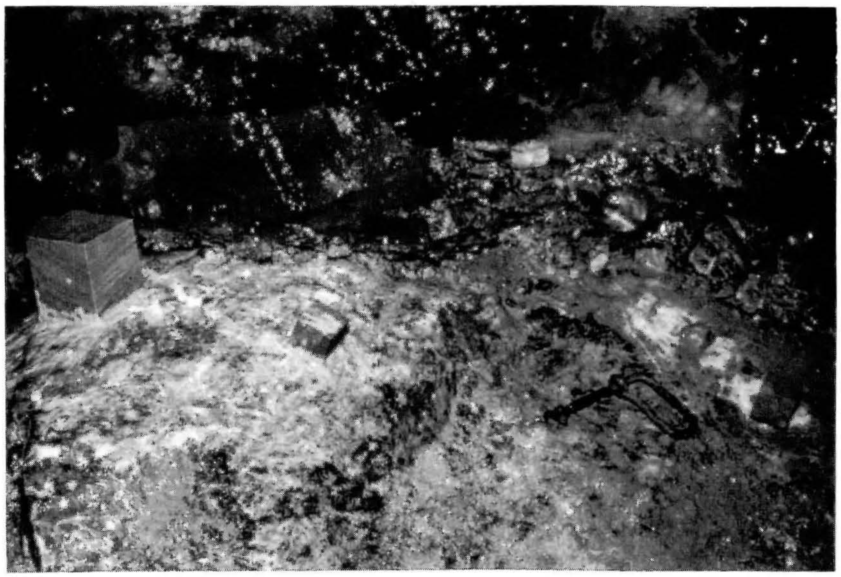


Fig. 35 - Photo of artificial obstacles that were fastened to the bedrock knob. From left to right, there is one 5-cm cube, a 2.5-cm cube, two 1-cm cubes, and another 2.5-cm cube.

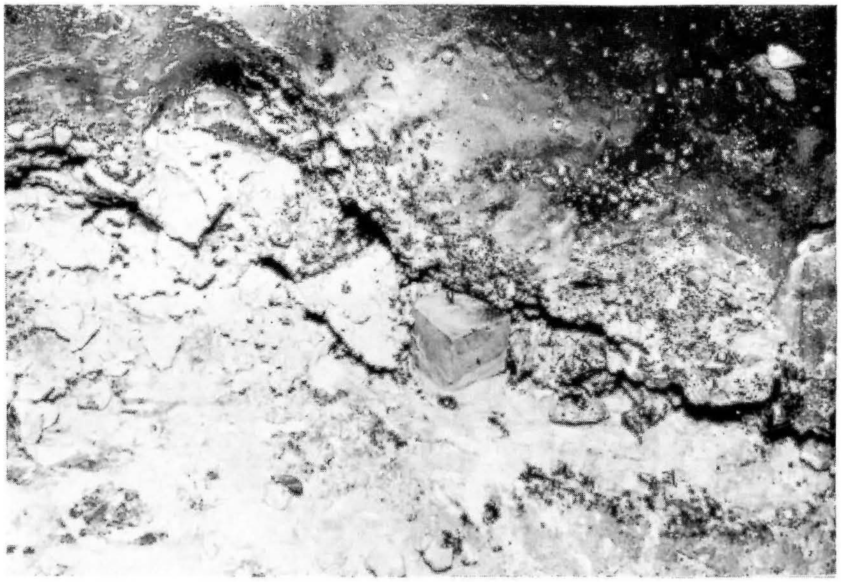


Fig. 36 - Photo of 2.5-cm cube with diagonal placed upglacier to reduce the compressive stress on the upglacier face. The ice is flowing toward the viewer.

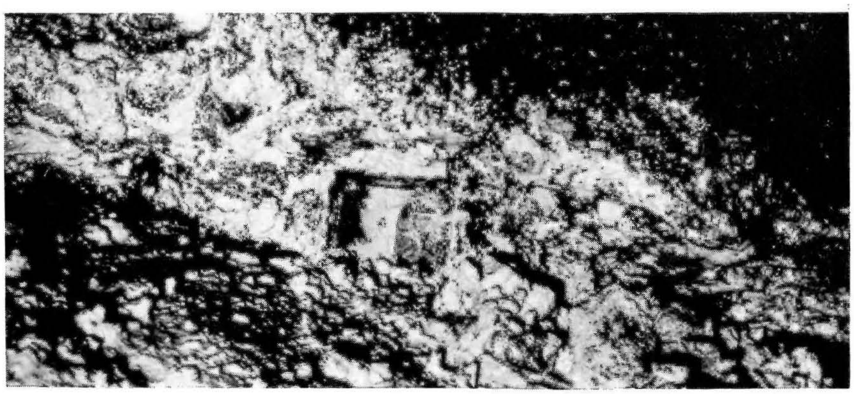


Fig. 37 - Photo of groove produced in the bottom of the glacier as the ice flowed past the 2.5-cm cube.

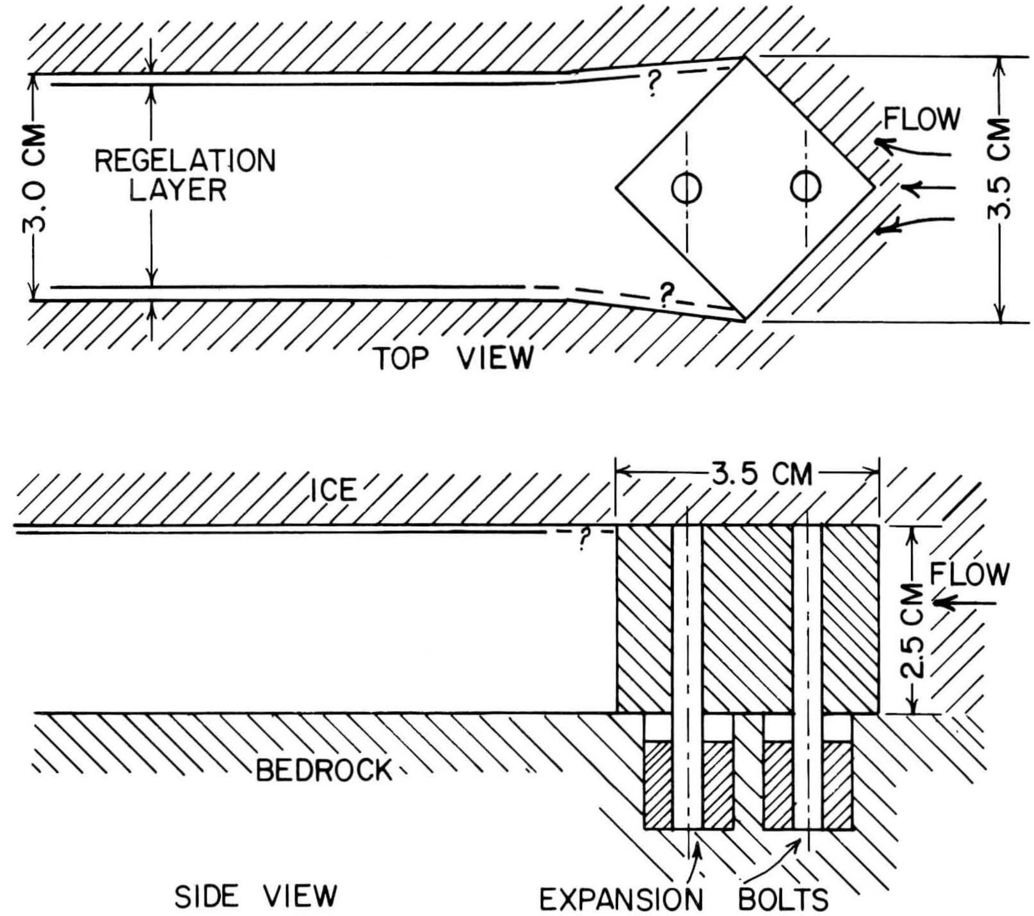


Fig. 38 - Diagram showing plan view and longitudinal view of groove in the ice behind the 2.5-cm cube.

Fig. 39 - Close-up of portion of regelation layer (between arrows) that lined the cavity behind the 2.5-cm cube.

The flow if ice around the side of a bedrock knob 1 m high and 3 m wide was observed in both 1966 and 1967. The ice which flowed around the side of the knob had a "ropy" appearance (Fig. 40) which suggested a turbulent-type of flow. As the ice moved around the knob, the groove exhibited about 10 cm of horizontal closure. The thin, clear layer of regelation ice was also present on the surface at this location.

These observations appear to support the calculated value of 1 cm for the controlling obstacle size. Above this size the thickness of the regelation layer remained constant. One question that remains to be answered is why there is no vertical closure of the grooves. It may result from the loss of the water which was produced by the pressure-melting mechanism.

Mechanics of Basal Sliding

Observations from Casement Glacier Tunnel

1. The bottom 10 to 30 cm of the wall in the tunnel consisted of alternating layers of regelation ice and debris (Figs. 41 and 42).

2. Rocks adhering to the bottom of the glacier were seen a number of times (Fig. 43). Figure 44 shows a rock which had been rotated from its original orientation by an encounter with some obstacle. It was possible to detach it and rotate it back through the groove to its original position.

3. Rocks wholly within the ice except for the bottom which had been exposed by friction and pressure melting were often seen. In every case there was a cavity on the downglacier side of the rock indicating that it had been held up temporarily while the ice flowed around it (Fig. 45). In some cases the rock was fractured into smaller pieces that could accommodate the flow over the obstacle (Fig. 46).

4. There was debris on the downglacier side of every bedrock knob. The quantity of debris increased during the period of the investigation because the excavation of the tunnel raised the temperature in the cavity from below 0°C to a few degrees above 0° resulting in the melting out of debris from the basal layer and its deposition on the bedrock knobs.

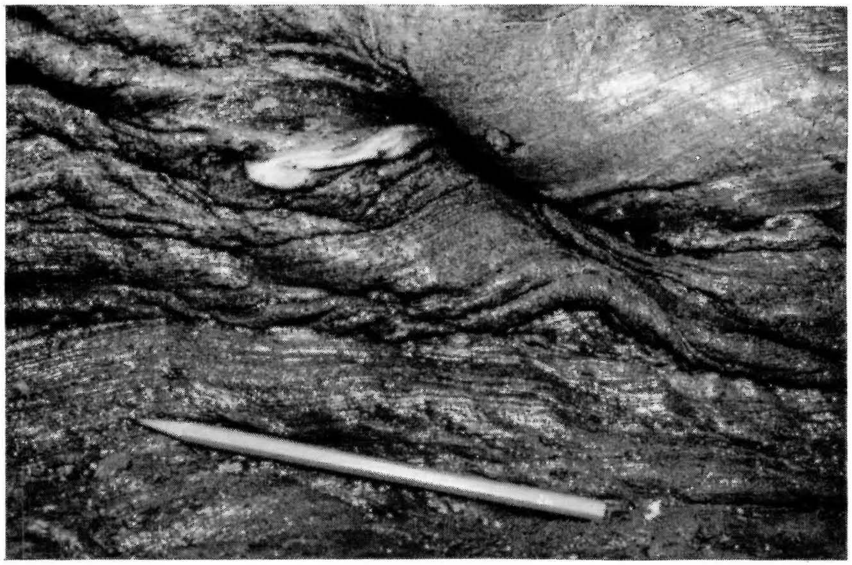


Fig. 40 - Feature in glacier cave wall about 20 m inside Casement Glacier showing the "ropy structure" of the basal ice layer as it is squeezed around the side of a bedrock knob. Ice flow is from right to left. The shiny appearance of the wall is a result of the camera flash reflecting from the thin layer of clear regelation ice.

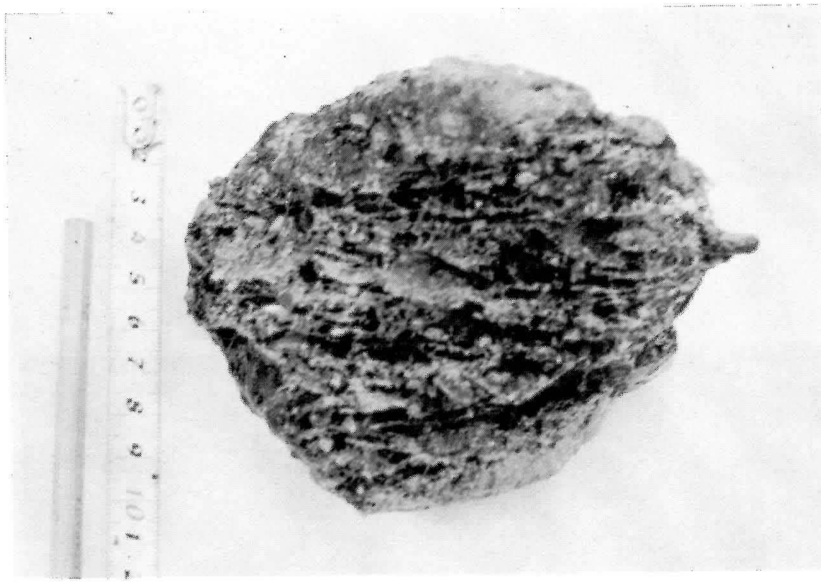


Fig. 41 - Photo of piece of ice excavated from the debris-rich layer at the bottom of the glacier. Notice the alternation of the layers of debris and regelation ice.

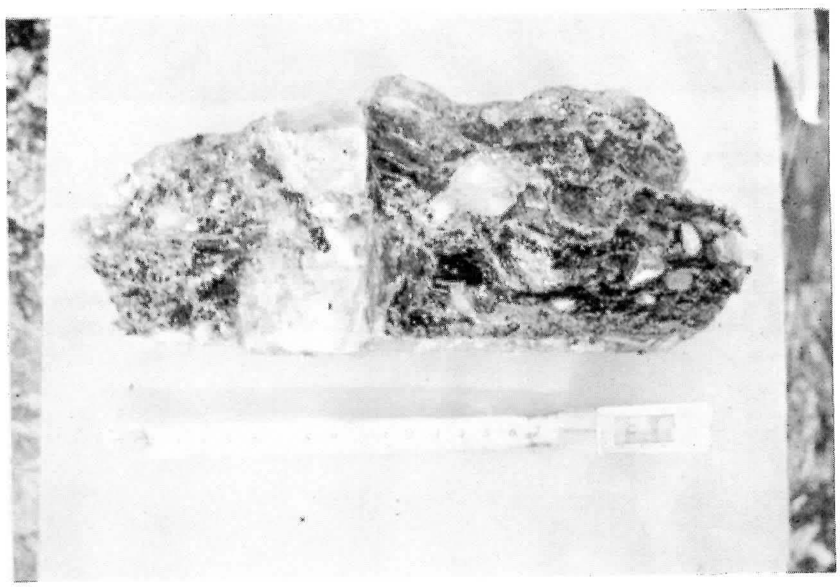


Fig. 42 - Photo of section of basal ice showing 0.75-cm layer of regelation ice at bottom.

Fig. 43 - Photo of two rocks that were found stuck to the bottom of the glacier on the downglacier side of a bedrock knob. They obviously had been attached to the bottom since the ice passed over the bedrock knob in the background, about 3 m away. The rocks are 7.5 and 5 cm in width.

Fig. 44 - Photo of rock fastened to the bottom of the glacier that had been rotated in a subsequent encounter with some obstacle. The rock could be detached and rotated through the groove in the ice to its original position at the time of initial attachment. Ice flow is from right to left.

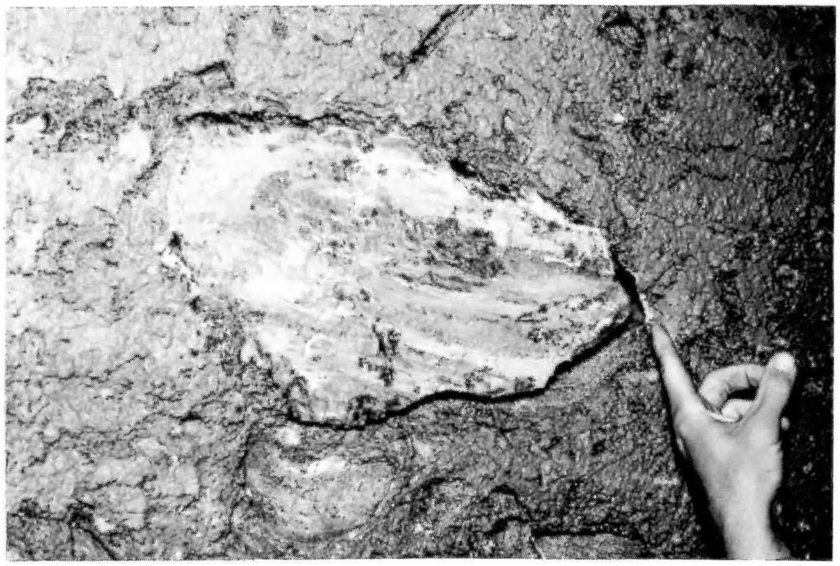


Fig. 45 - Rock exposed in the bottom of the glacier that had been held up temporarily by a bedrock knob. The cavity to which the finger is pointing resulted from the continued movement of the ice (flow is from left to right). The light-colored streaks on the rock are smears of rock flour produced by abrasion on the bedrock.

Fig. 46 - Photo of large rock fragment (larger than 0.5 m) that was fractured into smaller pieces by the compressive and shear stresses exerted on it by the ice when it was caught on a bedrock knob. The ice flow is toward the viewer.

Discussion

The alternation of layers of debris and regelation ice immediately suggested that it was a composite of the ice produced by the pressure-melting process and the accumulation of debris picked from the cavities downglacier from the knobs. This idea was lent support by the observation of rocks and other debris adhering to the ceiling of the cavity (the bottom of the glacier). Presumably, this material was frozen to the bottom of the glacier by regelation upon the release of pressure on the downglacier side of the knobs, or, possibly, by vertical closure during the winter when the sliding velocity was lower. By a repetition of this process of sliding over knobs (see Fig. 47) producing the thin layer of regelation ice, and then adding material at the bottom by whatever mechanism that is operative, this observed basal layer could have been produced.

Formation of "Till Curls"

On the upglacier side of the knob most intensively studied, the debris layer was 30 cm thick, but it thinned to 10 cm as the ice flowed over the top of the knob. The layer of basal debris that was squeezed between closely-spaced, adjacent knobs was as much as 1 m thick. The extra debris-laden material seemed to be squeezed plastically around the knobs, producing a measurable increase in debris-layer thickness between adjacent knobs (sites I and II in the 1967 study were on separate knobs that were 2 m apart). Observations of a set of dowels placed in the wall of the tunnel over the bedrock knob in 1966 suggest that the vertical strain rate in this bottom layer is 3.96 per year.

As this thickened layer of basal, debris-laden ice is squeezed around the knobs and moves downglacier over the cavity and away from the support of the bedrock, it becomes detached from the overlying clean, normal glacier ice and falls away very slowly from the bottom of the glacier. These features (Fig. 48) were named "till curls". Similar features have subsequently been observed in a cave under the ice on Anvers Island, Antarctica (G. Dewart, personal communication). These features probably are common at the base of glaciers, but because of the limited number of investigations that have been made in cavities beneath glaciers, they had not been observed. They would not produce any distinctive remnant deposit that could be distinguished as to its origin.

Conclusions

From the results of the two summers' work in the ice tunnel in Casement Glacier, the following conclusions have been drawn concerning the basal sliding process:

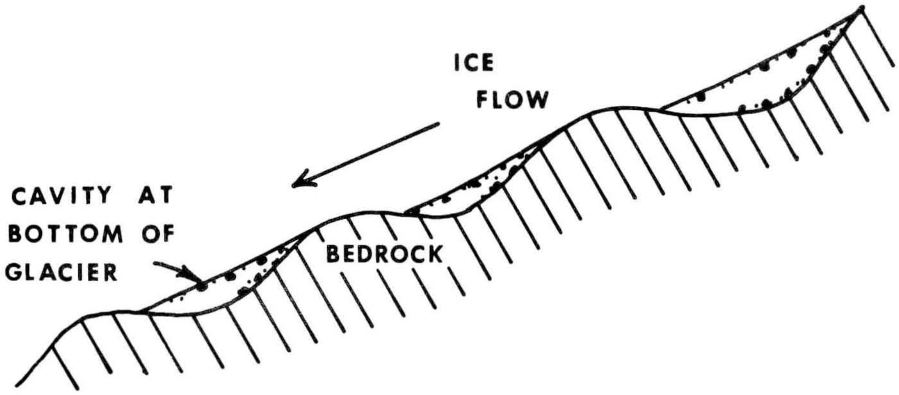


Fig. 47 - Diagram showing a series of cavities at the bottom of a glacier illustrating how the observed alternation of debris and regelation layers could be produced.

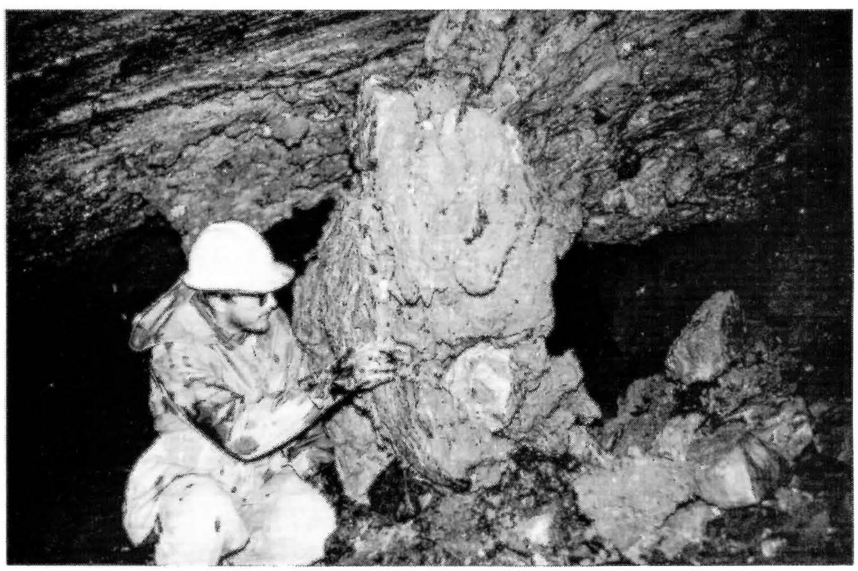


Fig. 48 - Photo of "till curl" about 15 m inside glacier cave in Casement Glacier. Ice flow is from right to left.

1. If there is any "stick-and-slip" motion at the bed of a glacier, it does not result in jerky motion more than a few centimeters above the bed as none was observed in either the 1-1/2 or the 24-hour studies. Therefore, any observed jerky movements on the surface probably result from rupture (shearing and the opening of crevasses) when the build-up of stresses exceeds the breaking limit.

2. Measurements of slip rate in the tunnel verify the suggestion that the observed annual, seasonal, and diurnal changes in surface velocity can be attributed, at least in part, to changes in the basal sliding rate, which is a function of the quantity of water at the base of the glacier, from melting and precipitation.

3. Both regelation slip and plastic flow are important processes in basal sliding, with plastic flow becoming predominant for obstacle sizes greater than the critical size, which is greater than 1 cm but less than 2.5 cm.

Suggestions for Future Tunnel Investigations

The problem of variation of slip rates should be investigated more closely by measuring sliding rates and surface velocities simultaneously. The best approach to this problem would be the adaptation of a sensitive micrometer to a recording instrument so that the investigators will be free to make accurate measurements of short-period changes in surface velocity. Perhaps with these data, the time lag between the period of maximum ablation at the surface and the maximum slip rate at the bed can be determined. The use of an inclinometer in a hole drilled through the glacier into the tunnel would provide valuable data on the variation of velocity with height above the bed.

There appears to be some question as to whether there is stick-slip movement at the bed of the glacier. The existence of such features as chatter marks and other regularly spaced impact marks verifies the existence of this kind of movement. However, chatter marks are not common; whereas, continuous striations are. For this reason it would be of interest to determine how common the stick-slip movement is and under what conditions it occurs. This could be investigated by using a large number of recording micrometers near the bed at a variety of locations.

An accurate value of the compressive and shear stresses acting on the upglacier side of an obstacle would be valuable in understanding the mechanics of basal sliding. These parameters might be measured with the use of pressure sensitive instruments (see Figs. 49 and 50). These instruments could be calibrated in the laboratory so that the values observed in the field could be converted into terms of compressive and shear stress.

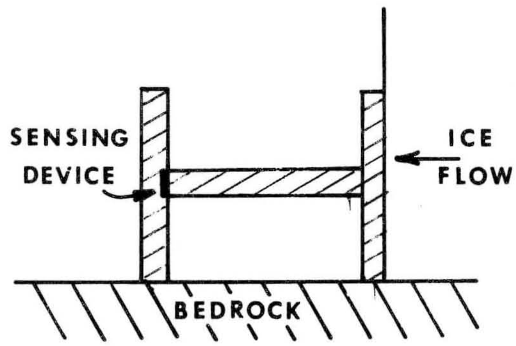


Fig. 49 - The back side of the device is fixed to the bedrock and the ice presses against the moveable front face which creates a compressive stress in the sensing device and alters its readout value.

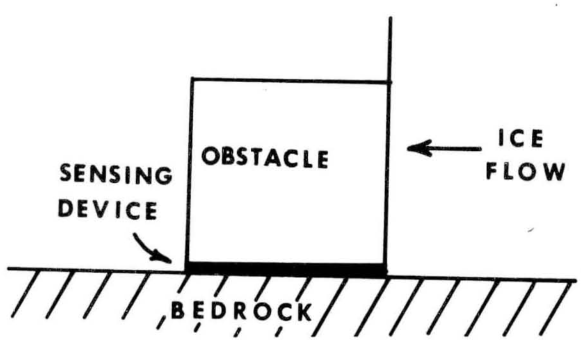


Fig. 50 - The cube is fastened to the bedrock by the device, the properties of which vary with the applied shear stress, τ.

Using this technique, the value of the compressive and shear stresses could be determined for a number of different sizes of obstacles to see how their values vary with increasing obstacle size.

The value of B, one of the constants in Glen's (1952, 1955) flow law for ice, is temperature dependent. It would be of considerable value to measure the deformation of the tunnel so that the values of the flow law constant may be derived. These values could be compared with those previously derived from tunnel studies (Haefeli, 1963).

The debris load at the bottom of the glacier should be studied more intensively, both in the field and in the lab, so that physical properties such as viscosity and coefficient of sliding friction can be determined for various debris-content conditions. In an extended study lasting for two or three years, it would be possible to measure the rate of erosion of the bed by measuring the change in depth of marks made in the bedrock. In a location such as that of the Casement Glacier tunnel, every fragment that came into contact with the bedrock could be examined and the total abrasive material could be related to the rate of erosion. It would be possible to establish a relationship between the rate of erosion and the amount of abrasive, the ice velocity, and the overburden pressure.

CHAPTER VIII

SHORT-TERM HEAT-BALANCE STUDIES

Introduction

Glacial-meteorology is concerned with the quantitative evaluation of the main sources of heat energy that contribute to the surface melting process on a glacier. The principal sources of heat energy are radiation from the sun and sky, conduction and convection from the overlying air mass, condensation of water vapor on the surface, and conduction from warmer ice below the surface. Another source is warm rain which falls on the glacier during the summer.

The energy is expended in a variety of ways. Among them are reflection of incident radiation from the glacier surface, radiation of long-wave radiation, energy conduction downward into the glacier, and sublimation or evaporation of the ice, snow, or water. The remainder of the energy is used to melt snow and ice at the surface of the glacier.

In general, the heat balance equation may be written as:

$$Q_R + Q_A + Q_L + Q_I + Q_P - Q_M = 0$$

where

Q_R = radiation,

Q_A = sensible heat, conduction and convection to or from the air layer above the surface,

Q_L = latent heat of condensation or evaporation,

Q_I = heat conducted into or out of the ice or snow,

Q_P = heat from rain,

Q_M = heat remaining for melting of ice or snow.

Another way this can be considered is by equating the heat sources to the heat sinks which, according to the Law of the Conservation of Energy, must be equal.

Heat Sinks		Heat Sources
Snow/ice melt (Q_M)		Radiation (Q_R)
+		+
Evaporation (Q_L)	=	Sensible heat (Q_A)
+		+
Heat conduction into snow/ice (Q_I)		Condensation (Q_L)
		+
		Precipitation (Q_P)

Two heat-balance studies, each of four days duration, were conducted on Casement Glacier near marker 11-2. The studies ran from 0000 hours, 31 July to 2400 hours, 3 August and from 0000 hours, 27 August to 2400 hours, 31 August. Half-hourly observations were made of net radiation, wet and dry bulb temperatures at two levels with aspirated psychrometers, met screen temperature, precipitation, cloud cover, and weather developments.

Computation of Individual Terms in the Heat Balance Equation

Radiation

The contribution of radiation, Q_R, to the heat balance equation can be expressed as the algebraic sum of the short-wave and long-wave radiation. For short-wave radiation, snow possesses a high albedo (as high as 0.95), but for long-wave radiation it behaves as a blackbody, the peak of the emission spectrum at 273°K being around 10μ. Of the incident long-wave radiation, practically all is absorbed at the surface. However, long-wave radiation is also emitted from the surface of the glacier. This outgoing radiation frequently results in a net loss of energy overnight.

Calculation of Q_R

A Funk net radiometer (Inst. no. 274) was used to measure the net radiation during the studies. This instrument is designed to measure the net radiation flux as the algebraic sum of the output of upward and downward facing thermopiles. The measured value each half-hour was considered to be representative for the period.

Turbulent Transfer of Sensible and Latent Heat

Sensible heat, Q_A, is that energy exchanged at the surface of the glacier by convection and conduction to or from the overlying layer of air. The equation for the calculation of the contribution of sensible heat may be written:

$$Q_A = c_p \, A \, \frac{d\theta}{dz} \, t$$

where

- c_p is the specific heat of air at constant pressure (0.24 g-cal/g°C)
- A is the exchange coefficient (g/cm sec),
- $\frac{d\theta}{dz}$ is the vertical gradient of the potential temperature (taken as observed °C/cm),

t is the time interval in seconds.

The exchange coefficient, A, governs the exchange of heat and water vapor above the surface (Wallén, 1948). It is assumed that the wind, temperature, and vapor pressure profiles may be represented by power laws. This assumption seems to be valid (Wallén, 1948; Andrews, 1964); however, others suggest that a logarithmic law may be more accurate (Havens and others, 1965; Grainger and Lister, 1966). A general statement of the power law may be given as follows:

$$\frac{\alpha_2}{\alpha_1} = \left(\frac{Z_2}{Z_1}\right)^{1/n_\alpha}$$

where α is the element (wind, temperature, vapor pressure) and the subscripts refer to the height above the surface ($z_1 < z_2$). Using this equation, values for the power law indices for the wind, n_u, temperature, n_θ, and vapor pressure, n_e, were calculated for each half-hour interval.

A general expression for A at height z can be written (Havens, 1964):

$$A_z = ku_z z^{\left[(n_\theta - 1)/(n_\theta) - (1/n_u)\right]}$$

where k is a constant.

The value of k has been determined for a number of sites:

$k = 1.8 \times 10^{-4}$ Kärsa Glacier

$k = 1.6 \times 10^{-4}$ Salisbury Plain

$k = 1.5 \times 10^{-4}$ the sea

$k = 1.4 \times 10^{-4}$ Isachsen Plateau

The value 1.8×10^{-4} that was calculated by Wallén (1948) for Kärsa Glacier was chosen as most representative of the conditions on Casement Glacier.

The value of A was calculated for each half-hour period using the corresponding values of n_u, n_θ, and u_z. This value was then used for the calculation of Q_A for that period.

The latent heat contribution to the heat balance, Q_L, is that energy released by condensation on, or evaporation from, the surface of the glacier. The sign and rate of transfer of this energy depends upon the wind, temperature, and vapor pressure profiles. The transfer of latent heat per unit time may be expressed as follows (Andrews, 1964):

$$Q_L = L\,A\,\frac{0.623}{p}\,\frac{de}{dz}\,t$$

where

L is the latent heat of condensation/evaporation (600 g-cal/g),

p is the atmospheric pressure (mmHg),

de/dz is the vertical gradient of vapor pressure (mmHg/cm).

Conduction of Energy through the Snow and Ice

The heat flow per unit time may be treated as an elementary problem in linear heat conduction and may be stated as:

$$Q_I = C\ T(Z)dz\ \rho$$

where

ρ = the density of ice (0.9 g/cm^3),

C = specific heat conductivity (0.48 cal/g/°C),

T = the change in temperature over the depth Z.

However, if the ice is temperate and the winter cold wave has already been restored by summer melting, there will be no conduction of heat energy into the ice because there would be no thermal gradient. Since this was the case at Casement Glacier, this term was not considered in this analysis.

Precipitation

The contribution of precipitation, Q_P, to the heat balance can be important in rainy areas like southeast Alaska. The heat energy derived from precipitation is:

$$Q_P = C_w(T_p - T_s)P$$

where

C_w = specific heat of water (1 cal/g°C),

T_p = temperature of the precipitation (taken as air temperature),

T_s = temperature of the surface (0°C),

p = precipitation (g/cm^2).

Computation of Terms

A computer program was written in Fortran IV to read the half-hourly values of the observations and to compute the individual terms in the heat balance equation. These data are given in Appendices E and F, respectively.

Summary of Results

Heat Sources

The heat balance has been calculated for 24-hour periods at half-hour intervals. The heat sources for each day and the two 4-day periods are summarized in Table 8 and Figure 51. More than half of the heat energy (65%) came from radiation (Q_R), while sensible heat (Q_A) and latent heat (Q_L) also made significant contributions to the heat balance (19 and 15%, respectively). The most important heat sink is the melting of the glacier. The heat lost by conduction through the ice was considered to be negligible.

TABLE 8

SUMMARY OF HEAT BALANCE COMPUTATIONS, CASEMENT GLACIER

Day	Q_R		Q_A		Q_L		Q_P		Q_M
	(ly)	(%)	(ly)	(%)	(ly)	(%)	(ly)	(%)	(ly)
Period One, 31 July - 3 August									
July 31	173.6	62	51.5	18	54.5	19	1.2	0	280.9
August 1	151.6	58	40.1	15	65.4	25	6.0	2	263.1
August 2	245.9	72	34.4	10	57.8	17	2.9	1	341.0
August 3	383.1	77	67.0	14	44.8	9	0.0	0	494.0
Totals	954.2	69	193.0	14	222.5	16	10.1	1	1379.0
Period Two, 26 - 29 August									
August 26	81.1	49	32.8	20	41.0	25	9.9	6	164.8
August 27	236.3	74	46.1	14	35.6	11	0.8	0	318.8
August 28	192.3	63	83.4	28	27.5	9	0.0	0	303.2
August 29	184.1	51	114.4	32	61.6	17	1.7	0	361.8
Totals	693.8	60	276.7	24	165.6	15	12.4	1	1148.5
Totals for combined periods									
	1648.0	65	469.7	19	388.1	15	22.5	1	2527.5

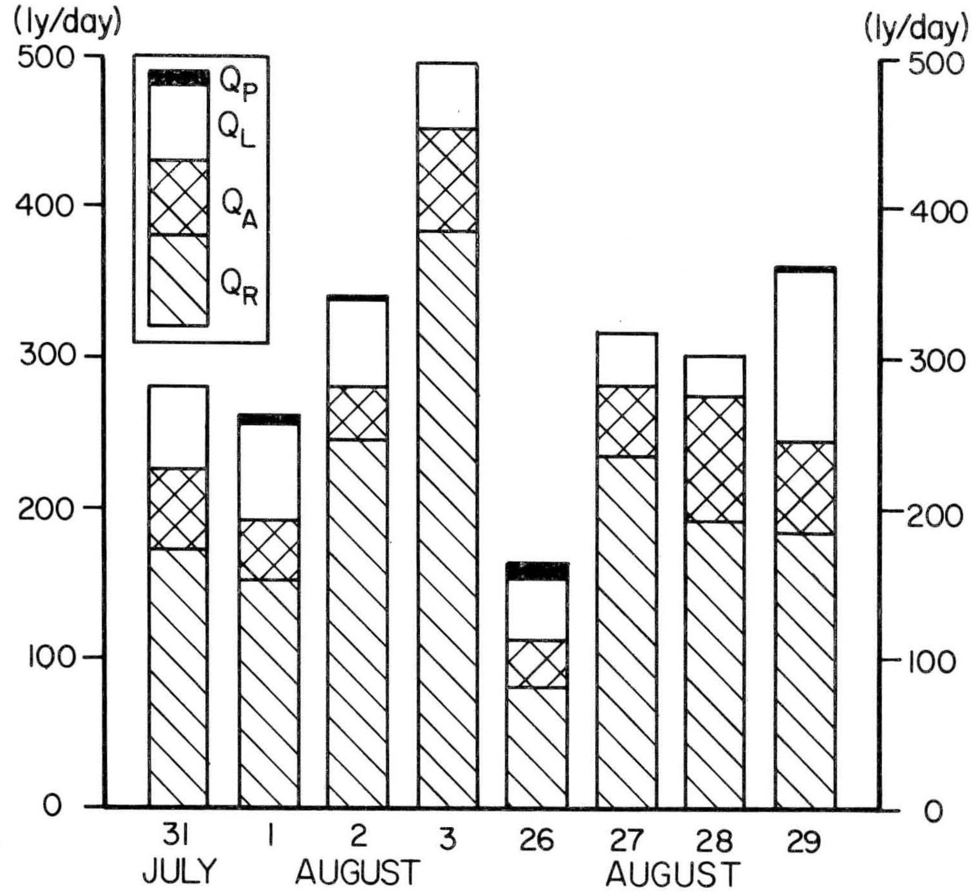


Fig. 51 - Graph showing the daily contributions of the terms in the heat balance equation during the two studies.

Comparison of Computed and Measured Ablation

The algebraic sum of the heat balance components represents the residual energy (Q_M) available to melt the ice or snow. Taking the heat of fusion of ice to be approximately 80 langleys (g cal/cm^2), the thickness of a layer of ice which would be melted can be calculated. The values of the measured and calculated ablation for the periods of the study are shown in Table 9. The agreement is reasonably good for the 4-day periods and for each day, except 3 August. The calculated values are within one standard deviation of the measured values.

TABLE 9

MEASURED AND COMPUTED ABLATION

Date	Measured (gm water)	Computed (gm water)	Difference (H_c - H_o)	Weather
Period One				
July 31	3.10	3.5	0.4	Overcast
August 1	3.45	3.4	-0.15	Overcast with rain
August 2	4.00	4.3	0.3	Overcast, rain in AM
August 3	3.80	6.2	2.4	Clear
Totals	14.35	17.3	2.95	
Period Two				
August 26	2.65	2.1	-0.55	Overcast, rain
August 27	3.40	4.0	0.60	Clearing
August 28	3.15	3.8	0.65	Cloudy by midmorning
August 29	4.45	4.5	0.05	High overcast
Totals	13.65	14.4	0.75	

It has already been mentioned in the short-term ablation section of this report that the error in the measured value of ablation depends upon the prevailing weather. Of the days during which observations were made, measured ablation exceeded the calculated value only twice, on days which were overcast with rain. For the other days the calculated ablation is higher than the measured value.

Discussion of Results

There are several possible sources of error in the calculation of the heat-balance components. The first is the assumption that the variation of windspeed, temperature, and vapor pressure with height above the surface of the glacier may be expressed by the power law formula. This assumption is certainly not without precedent. However, Havens and others (1965), in a critical examination of the methods of calculating the turbulent heat flux, suggest that logarithmic profiles give the most accurate estimate of the energy transfer. They emphasize, however, that any mathematical formulation for the expression of the variation of windspeed, temperature, and vapor pressure near the ground is, itself, only an approximation. In fact, there have been cases reported for which neither the exponential nor the logarithmic laws could fit the data (Caisley and others, 1963).

To compare the effect of using the logarithmic law instead of the power law for the calculation of Q_A and Q_L, the computer program was altered so that the contribution of the turbulent transfer terms could be re-evaluated. The results of this are presented in Table 10 along with a comparison with the values calculated from the power law. The calculated ablation from the power law assumption fits the observed ablation data better than those from the log law (see Appendices G and H).

TABLE 10

COMPARISON OF THE HEAT BALANCE CALCULATIONS
BASED ON POWER LAW AND LOGARITHMIC LAW

Method	Q_R (%)	Q_A (%)	Q_L (%)	Q_P (%)	Q (ly)
Power law	65	19	15	1	2527
Log law	60	22	17	1	2747

The assumption that the radiation temperature and vapor pressure during the brief measuring period can be considered representative for the entire half-hour interval is thought to be reasonable because the weather conditions did not fluctuate rapidly during the periods of observation.

Another source of error is the assumed value of the constant k in the calculation of the exchange coefficient, A. Although this value is not really constant and varies from location to location, the resulting error in the calculation of the turbulent transfer terms would be small.

The assumption that the temperature of falling precipitation is equal to the screen temperature may not be valid, but it is a good approximation. Changes in the temperature of the precipitation by 10°C would not significantly alter the heat balance. Marangunić (1970), however, because of anomalously high ablation rates on rainy days, has suggested that falling precipitation has an additional effect. He has suggested that the spattering of the raindrops as they encounter the surface of the glacier effectively increases the turbulence in a very thin layer of air near the surface resulting in a greater exchange of energy than would be predicted by the standard equations for the calculation of the turbulent transfer terms.

Comparison with Similar Investigations

The results from the Casement Glacier heat-balance study are shown in Table 11 along with the results from similar investigations on glaciers at approximately the same latitude.

TABLE 11

COMPONENTS OF THE HEAT BALANCE AT CASEMENT GLACIER
COMPARED WITH SIMILAR INVESTIGATIONS AT OTHER GLACIERS

	Q_R	Q_A	Q_L
Casement Glacier 1050 m	65	19	15
Sherman Glacier 480 m (Marangunić, 1970)	64	22	12
Salmon Glacier 1700 m (Adkins, 1958)	75	15	10
Blue Glacier 2010 m (LaChapelle, 1959)	69	25	6
Worthington Glacier 850 m (Streten and Wendler, 1968)	51	29	20
Kärsa Glacier <1100 m (Wallén, 1948)	55	29	16

CHAPTER IX

SUMMARY AND SUGGESTIONS FOR FUTURE RESEARCH

Measurements made on Casement Glacier during the summers of 1965, 1966, and 1967 revealed time-variations in the horizontal component of the surface velocities. The summer velocities were greater than the winter velocities. The magnitude of the summer velocities varied from year to year but were always greater than the winter velocity. These changes in surface velocity correspond to changes in the basal sliding velocity as measured in an ice tunnel along the margin of the glacier.

The mass budget of the glacier for the glaciological year 1966-1967 was determined to be $-235 \pm 46 \times 10^9$ kg. Discharge and budget measurements were calculated for two sections of the glacier, between lines 2 and 3, and between lines 8 and lines 9, 11, 12, and 13. The mass budget of each section was negative, being -8.4×10^9 kg and -9.1×10^9, respectively.

Englacial velocities were calculated at each of the stakes for which the ice thickness had been determined by gravity and the surface velocity by surveying. Using these velocity data, the vertical components of the surface velocity, the longitudinal ice thickness profile, the trajectory of a layer of ice was calculated from line 14 through to line 2, a distance of 14.4 km. The estimated travel-time for this motion would be approximately 140 years.

Two short-term heat-balance studies, of four days duration each, were conducted on the glacier in 1967. The contribution of each component of the heat balance equation was computed in two different ways: first, using the assumption that the variation of the wind speed, temperature, and vapor pressure follows the power law, and second, assuming a logarithmic variation. The calculated results were compared with the observed values of the ablation during the corresponding periods. The values determined by the power law fit the observed ablation data better than those calculated from the logarithmic law. For the two studies the relative contributions of Q_R, Q_A, Q_L, and Q_P were 65, 19, 15, and 1%, respectively.

Investigations were made in an ice tunnel on the variations in slip rate and the mechanics of basal sliding. Basal sliding at the point of observation in the tunnel was a continuous process; there was no jerky, stick-slip movement and any observed jerky movement on the surface would result from fracture and shearing of the surface ice. The rate of sliding is affected by changes in the quantity of lubricating water at the bed and most of the observed annual, seasonal, and diurnal changes in surface velocity result from changes in the quantity of free water at the bed of the glacier. Artificial obstacles were placed on a bedrock knob and the mode of flow of ice around them examined. It was determined that the critical size at which the contribution of regelation slip equals that of plastic flow is between 1 and 2.5 cm.

One of the most critical aspects of glaciological investigation is the glacier itself. Care must be taken to choose a glacier that is both representative and of workable size. Of course these considerations must be weighed against the purpose of the program, but the selection of a glacier should not be made lightly as the success of the project depends to a large extent on this decision.

Future glaciological research should try to resolve the following problems:

1. More detailed data are needed on the time variations of ice velocity at the top, the bottom, and within the glacier. This would lead to a greater understanding of the mechanics of glacier flow. This would require accurate measurements of short-term surface and basal velocities (as discussed in Chapter VII) and measurements of seasonal changes in surface, englacial and basal sliding velocities at the same location.

2. An accurate, convenient method for measuring daily ablation should be devised so that comparisons of measured ablation and calculated ablation derived from heat-balance studies will be more meaningful. Other problems concerning daily ablation which should be investigated are the mechanics of the ablation of polycrystalline ice and the micrometeorology of the layer of air just above the surface of the glacier.

3. The variation of velocity with depth should be measured under varying conditions of ice thickness, surface slope, and surface velocity and the results compared with calculated values from Nye's equation. The measurement of this parameter depends to a large extent upon the development of an inexpensive, easily constructed, portable drill for drilling large numbers of holes through glaciers and an inclinometer for measuring the changes in slope, so this project should be given high priority.

4. The mechanics of basal sliding of temperate glaciers is still not fully understood, although the writer of this report has attempted to resolve some of the problems. A full discussion of the problems of basal sliding which should be investigated is given in Chapter VII of this report. Let it suffice to say that accurate measurement of the stress conditions at the bottom of the glacier and detailed measurements of the time-variations in sliding velocity should receive the most immediate attention.

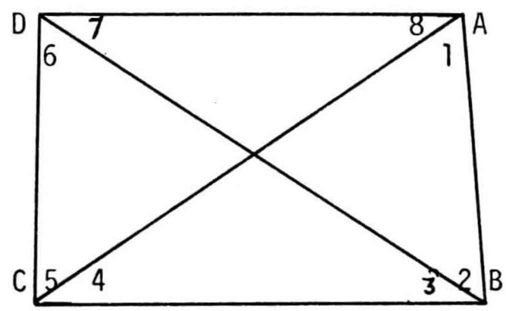
5. Additional observational data on meteorology, heat balance and their relationship to each other and to the surface ablation will always be valuable in attempting to understand the complex processes affecting the nourishment and wastage of glaciers.

APPENDICES

APPENDIX A

ADJUSTMENT OF TRIANGULATION FIGURES

Part 1 - Quadrilaterals



Angle No.	Adjusted Angle °	'	"	Amount Adjusted "	Angle No.	Adjusted Angle °	'	"	Amount Adjusted "
1-3-2-7									
1	85	22	41	-02	5	70	18	23	+01
2	12	14	15	+01	6	27	18	33	+03
3	19	40	27	+05	7	14	39	44	-07
4	62	42	37	+06	8	67	43	20	-06
4-7-8-3									
1	41	31	21	+07	5	46	19	46	+01
2	55	47	23	+00	6	50	58	58	-06
3	37	21	30	+07	7	52	23	36	+01
4	45	19	46	-02	8	30	17	40	-08
4-7-8-13									
1	41	31	17	+03	5	34	52	40	-02
2	31	10	32	+03	6	37	49	09	-03
3	61	58	24	+00	7	38	51	39	+01
4	45	19	47	-01	8	68	26	32	+00

APPENDIX A - Continued

Angle No.	Adjusted Angle °	'	"	Amount Adjusted "	Angle No.	Adjusted Angle °	'	"	Amount Adjusted "
<u>4-7-5-13</u>									
1	16	29	27	+00	5	34	30	41	+00
2	34	52	43	+01	6	16	51	29	+00
3	53	41	12	+02	7	76	40	49	-02
4	74	56	38	+02	8	51	57	01	-02
<u>13-5-9-12</u>									
1	22	13	26	+02	5	30	08	00	+01
2	26	25	16	+01	6	18	30	43	+00
3	53	12	55	+02	7	59	40	12	+00
4	78	08	22	+02	8	71	41	06	+00
<u>15-10-16-11</u>									
1	45	19	09	+08	5	66	02	05	-04
2	50	37	26	+04	6	29	54	30	-08
3	19	32	20	+00	7	53	47	42	+08
4	64	31	05	-07	8	30	15	43	+04
<u>17-10-18-19</u>									
1	32	13	00	-01	5	39	42	02	+24
2	47	45	43	+00	6	40	16	24	+08
3	45	38	23	+04	7	65	21	27	+10
4	54	23	11	-07	8	34	40	07	-02
<u>21-18-20-22</u>									
1	39	56	30	+08	5	36	33	20	+03
2	17	33	51	-02	6	20	57	01	-07
3	44	27	42	+01	7	22	51	54	+12
4	78	01	57	-02	8	99	37	45	+05

APPENDIX A - Continued

Part 2 - Triangles

Angle	Unadjusted angles			Angle	Adjusted angles		
	°	'	"		°	'	"
4-7-6							
4	80	14	15	4	80	14	13
7	46	01	05	7	46	01	03
6	53	44	46	6	53	44	44
	179	59	66		179	59	60
7-13-14							
7	31	05	15	7	31	05	12
13	48	09	52	13	48	09	49
14	100	45	02	14	100	44	59
	179	59	69		179	58	120
12-9-11							
12	59	36	29	12	59	36	28
9	72	11	11	9	72	11	10
11	48	12	23	11	48	12	22
	179	59	63		179	59	60
12-15-11							
12	48	33	02	12	48	33	01
15	85	07	15	15	85	07	15
11	46	19	45	11	46	19	44
	179	59	62		179	59	60
16-10-17							
16	51	30	24	16	51	30	15
10	00	36	34	10	00	36	25
17	127	53	30	17	127	53	20
	178	119	88		178	119	60
18-21-19							
18	29	44	17	18	29	44	24
21	29	18	21	21	29	18	27
19	120	119	02	19	120	57	09
	178	119	40		178	119	60

Angle	Unadjusted angles °	'	"	Angle	Adjusted angles °	'	"
21-22-24							
21	68	10	32	21	68	10	36
22	72	47	06	22	72	47	10
24	39	02	10	24	39	02	14
	179	59	48		179	59	60
22-24-23							
22	30	52	20	22	30	52	27
24	15	32	20	24	15	32	27
23	133	34	58	23	133	34	06
	178	118	98		178	119	60
22-24-25							
22	29	30	20	22	29	30	15
24	14	35	01	24	14	34	56
25	135	54	54	25	135	54	49
	178	119	75		178	118	120

APPENDIX B

FORTRAN IV PROGRAM FOR ANALYSIS OF ERRORS IN SURVEY

```
C  SURVEY ERROR ANALYSIS PROGRAM
      DIMENSION NAME(50),BL(50),BLNU(50),BLCF(50), ERBL(50),ANRAZB(50)
      REAL  NDEG,NMIN,NSEC,NAR,ODEG,OMIN,OSEC
      INTEGER BLNU,BLCF   ,BLID
      ERANG=.000024
      READ (5,1) NBL,NAME(1),BL(1),ERBL(1)
    1 FORMAT (I3,A5,F9.3,F7.3)
      WRITE (6,100) HEADIN
  100 FORMAT (1H1,9X,47HERRORS IN THE COMPUTED LENGTHS OF THE BASELINES/
     11H0,9X,8HBASELINE,2X,6HNUMBER,3X,9HPRECEDING,2X,9HLENGTH OF,5X,14H
     1COMPUTED ERROR/1H ,9X,7HEND PTS,13X,8HBASELINE,3X,12HBASELINE (N),
     13X,15HIN BASELINE (M))
      WRITE (6,101) NAME(1),BL(1),ERBL(1)
  101 FORMAT (1H0,A5,F36.3,F15.3)
      IM1=I-1
      DO 10 I=2,NBL
      READ (5,2)  NAME(I),BLNU(I),BLCF(I),BL(I),ADEG,AMIN,ASEC,ODEG,OMIN
     1,OSEC,TDEG,TMIN,TSEC
    2 FORMAT (A5,2I3,F10.3,F4.0,2F3.0,2(F5.0,2F3.0))
      ANRAZB(I)=ANRAD(ADEG,AMIN,ASEC)
      ANRAON=ANRAD(ODEG,OMIN,OSEC)
      ANRATH=ANRAD(TDEG,TMIN,TSEC)
      ERBL(I)=BL(I)*SQRT(((ERBL(IM1)/BL(IM1))**2)+0.6667*(( 5.0 /206264.
     18)**2)*(((COS(ANRAON)/SIN(ANRAON))**2)+((COS(ANRATH)/SIN(ANRATH))
     1**2)+((COS(ANRON)/SIN(ANRON))*(COS(ANRATH)/SIN(ANRATH)))))
   10 WRITE (6,102) NAME(I),BLNU(I),BLCF(I),BL(I),ERBL(I)
  102 FORMAT (1H ,9X,A5,I10,I9,F17.3,F15.3)
      WRITE (6,110)
  110 FORMAT(1H1,10X,54HERRORS IN THE X AND Y COORDINATES OF THE SURVEY
     1STAKES/1H ,10X,42HRESULTING FROM A FIVE SECOND ANGULAR ERROR/1H0,1
     10X,6HMARKER,2X,13HERROR    ERROR/1H ,12X,2HNO,4X,4HIN X,4X,4HIN Y/1
     1H )
      DO 11 K=1,40
      READ (5,3) NSTA,BLID,PDEG,PMIN,PSEC,NDEG,NMIN,NSEC,DDEG,DMIN,DSEC,
     1VEL
    3 FORMAT (A5,I3,3(F5.0,2F3.0),F7.2)
      I=BLID
      PAR=ANRAD(PDEG,PMIN,PSEC)
      NAR=ANRAD(NDEG,NMIN,NSEC)
      DIFR=ANRAD(DDEG,DMIN,DSEC)
      APM=PAR+ANRAZB(I)
      CMM=-NAR-ANRAZB(I)
      APC=PAR+NAR
      SAMSQ=(SIN(APC))**2
      ERXC=(BL(I)*ERANG/SAMSQ)*((SIN(NAR)*SIN(CMM)+SIN(APM)*SIN(PAR)))
      ERYC=(BL(I)*ERANG/SAMSQ)*((COS(APM)*SIN(PAR)-SIN(NAR)*COS(CMM)))
      WRITE (6,111)NSTA,ERXC,ERYC
  111 FORMAT (1H ,11X,A5,F6.3,F8.3)
   11 CONTINUE
      STOP
      FUNCTION ANRAD(JDEG,JMIN,JSEC)
      REAL  JDEG,JMIN,JSEC
      ANRAD=(JDEG+(JMIN+JSEC/60.)/60.)/57.2957795
      RETURN
      END
```

APPENDIX C

ICE VELOCITY DATA

Marker No.	Summer	Marker No.	Summer 1965	Marker No.	Summer 1965
1-3	48.89	3-1	123.69	5-1	62.08
1-4	85.05	3-2	137.39	5-2	122.66
1-5	73.64	3-3	144.05	5-3	131.71
1-6	54.49	3-4	143.97	5-4	140.47
1-8	43.77	3-5	132.82	5-5	138.07
		3-7	99.26	5-6	126.98
6-2	91.62	3-8	70.85	5-7	121.04
6-3	96.55	3-9	46.69	5-8	121.23
6-4	160.72			5-9	60.96
4-2	144.95	4-6	179.07		
4-3	151.26	4-9	97.15		
4-4	153.75				

Marker No.	Summer 1965	Winter 1965-66	July, 1966-July, 1967	Summer 1967	Mean
2-1	8.02	7.35	----	----	8.03
2-2	12.75	7.77	11.18	10.92	9.75
2-3	15.12	10.71	13.33	15.81	12.39
2-4	-----	20.98	15.04	17.84	17.72
2-5	21.75	19.86	16.26	19.93	18.25
2-6	70.64	-----	-----	-----	70.64
2-7	79.49	-----	63.76 -----	72.63	64.96
2-8	-----	78.25	74.05	85.53	76.58
2-9	96.98	81.48	79.17	85.78	81.24
2-10	93.67	-----	-----	-----	93.67
2-11	82.41	-----	-----	-----	82.41
2-12	79.56	-----	-----	-----	79.56

Marker No.	Summer 1966	Winter 1966-1967	Summer 1967	Mean
4-1	65.44	62.32	74.07	63.40
4-2	107.70	103.07	115.12	104.30
4-3	122.37	115.12	123.65	116.41
4-4	127.67	120.01	130.30	121.40
4-5	127.31	123.25	128.13	123.98
4-6	126.92	117.94	123.65	119.20
4-7	119.98	112.81	113.72	113.55

Marker No.	Summer 1966		Winter 1966-1967		Summer 1967	Mean
4-8	-----	77.24	-----		71.56	76.73
5-1	10.85		-----		-----	10.85
5-2	124.02		116.08		108.75	116.95
5-3	117.60		152.79		126.18	147.35
5-4	119.89		153.23		134.01	148.34
5-5	122.44		-----		-----	122.44
5-6	118.94		133.34		126.30	131.20
5-7	90.70		127.72		122.39	120.38
7-1	51.13		-----		-----	51.13
7-2	66.85		-----		-----	66.85
7-3	72.65		-----		-----	72.65
7-4	83.67		-----		-----	83.67
7-6	159.10		-----		-----	159.10
7-7	157.31		153.21		-----	157.31
7-8	131.19		124.85		-----	125.39
7-9	83.59		77.80		-----	78.30
7-10	17.93		14.86		-----	15.13
8-1	18.09		10.14		-----	10.38
8-2	44.63		40.41		-----	40.72
8-3	72.27		61.83		-----	62,79
8-4	85.93		89.81		-----	89.34
8-5	114.89		110.47		-----	110.87
8-6	131.98		122.99		-----	123.81
8-7	135.64		126.98		-----	127.77
8-8	120.02		130.41		128.70	129.34
8-9	134.81		129.29		128.49	129.60
8-10	127.30		119.54		114.13	119.41
8-11	115.46		106.36		106.42	107.09
8-12	86.03		81.75		82,95	82.23
8-13	50.07		43.10		45.33	43.96
9-1	-----	37.41	-----		-----	37.41
9-2	53.32		-----	49.13	-----	49.47
9-3	58.75		-----	54.08	-----	54.46
9-4	60.89		56.82		56.29	57.09
9-5	64.50		58.19		62.06	59.10
9-6	65.17		59.90		61.06	60.45
9-7	65.87		60.68		63.24	61.37
9-8	66.19		60.80		63.09	61.48
9-9	74.65		-----	60.18	-----	61.17
9-10	66.30		58.13		65.03	59.50
9-11	64.48		54.83		58.66	55.98
9-12	61.50		49.06		52.51	50.39
9-13	-----		-----		13.86	13.86
9-14	-----		-----		6.07	6.07

APPENDIX C--Continued

Marker No.	Summer 1966	Winter 1966-1967	Summer 1967	Mean
10-3	78.46	78.72	89.12	79.04
10-4	97.55	89.53	87.25	89.96
1 -5	99.37	91.81	88.48	92.10
10-7	95.15	86.81	89.19	87.74
10-8	90.27	81.20	84.60	82.29
10-9	83.65	75.26	79.97	76.43
10-10	74.17	64.85	69.05	66.05
10-11	37.49	47.80	50.57	47.19
11-1	17.86	----- 7.55	-----	8.30
11-2	41.45	33.40	37.64	34.48
11-3	60.77	50.62	53.25	51.71
11-4	75.76	59.95	61.19	61.12
11-5	71.53	62.04	67.12	63.31
11-6	7-.58	63.89	68.08	64.82
11-7	75.09	65.13	66.61	65.13
11-8	69.63	62.35	65.20	63.10
11-9	-----	54.30	57.54	54.60
11-10	30.55	-----	-----	30.55
12-3	86.41	81.11	83.17	81.72
12-4	84.37	80.80	80.45	81.00
12-5	78.24	76.25	74.92	76.25
12-6	72.04	68.31	65.18	68.23
12-7	66.69	58.87	59.14	59.43
12-8	48.50	42.67	45.77	43.42
12-9	19.96	18.38	18.97	18.56
12-10	6.56	3.91	5.76	4.26
13-1	32.98	-----	-----	32.98
13-2	47.31	36.96	49.64	39.20
13-3	64.79	52.26	51.96	53.14
13-4	75.87	63.08	66.24	64.35
13-5	75.94	68.82	71.86	69.70
13-6	-----	71.32	74.78	71.69
13-7	76.49	69.76	73.73	70.66
13-8	78.24	-----	-----	78.24

Marker No.	Summer 1967	Marker No.	Summer 1967
14-4	60.84	15-1	44.56
14-5	61.20	15-2	62.17
14-6	60.61	15-3	63.51
14-7	60.11	15-4	67.64
14-8	59.18	15-5	64.03
14-9	57.23	15-6	66.63
14-10	53.38	15-7	57.70
14-11	35.00		

APPENDIX D

GRAVITY REDUCTION DATA

Station	Elev. (m)	Δg (mgal)	Comb. Boug. (mgal)	Lat. Corr. (mgal)	Terr. Corr. (mgal)	Reg. Corr. (mgal)	Boug. Anom. (mgal)	Ice Thkns (m)
Line 1								
E. edge	231.5	00.00	00.00	.00	0.00	0.00	0.00	
1-1	262.0	-11.06	5.85	-.08	-4.50	0.64	9.15	130
1-2	268.4	-13.86	7.08	-.17	-5.00	1.06	10.89	154
1-4	295.6	-22.79	12.47	-.28	-5.11	1.91	14.36	203
1-5	301.2	-23.14	13.38	-.41	-5.12	2.34	12.95	183
1-6	310.9	-24.61	15.24	-.54	-5.13	2.85	12.19	173
1-7	312.3	-24.22	15.70	-.62	-5.00	3.06	11.08	157
1-8	319.7	-25.32	16.93	-.71	-4.99	3.32	10.77	152
1-9	326.7	-24.28	18.27	-.79	-4.50	3.49	7.81	111
C. 25	388.1	-30.20	29.40	-1.00	-2.46	4.25	0.00	
Line 2								
W. edge	301.4	0.00	0.00	.00	0.00	0.00	0.00	
2-1	331.3	-9.12	5.74	.05	-1.42	0.25	3.08	44
2-2	349.8	-16.11	9.29	.09	-2.25	0.50	8.48	120
2-3	361.9	-20.91	11.61	.13	-2.62	0.79	10.28	146
2-4	375.0	-27.09	14.12	.18	-2.83	1.09	14.53	206
2-5	382.4	-30.04	15.54	.23	-3.10	1.49	15.88	225
2-6	391.5	-33.65	17.29	.32	-3.35	2.08	17.31	245
2-7	398.5	-37.80	18.63	.40	-3.41	2.58	19.60	278
2-8	399.0	-38.63	18.73	.49	-3.33	3.27	19.47	276
2-9	401.5	-38.08	19.21	.57	-3.08	3.82	17.56	249
2-10	397.5	-36.93	18.44	.62	-2.79	4.12	16.54	234
2-11	392.7	-31.90	17. 2	.66	-2.21	4.51	11.42	162
2-12	391.1	-31.31	17.21	.67	-2.21	4.71	4.71	92
E. edge	360.0	-16.98	11.07	.72	+0.23	4.96	0.00	
Line 3								
E. edge	456.5	-15.71	10.92	.68	1.05	3.06	0.00	
3-1	478.1	-36.93	15.06	.60	-2.38	2.85	20.80	295
3-2	479.0	-38.89	14.37	.52	-2.72	2.23	24.49	347
3-3	478.6	-38.69	15.16	.45	-2.76	1.96	23.88	338
3-4	476.5	-38.22	14.76	.38	-2.70	1.68	24.10	341
3-5	474.5	-36.63	14.37	.33	-2.68	1.53	23.08	327
3-6	452.3	-29.97	10.11	.29	-2.39	1.22	20.74	294
3-7	440.8	-25.82	7.91	.22	-2.29	0.98	19.00	269
3-8	435.2	-23.16	6.83	.17	-2.35	0.70	17.81	252

Station	Elev. (m)	Δg (mgal)	Comb. Boug. (mgal)	Lat. Corr. (mgal)	Terr. Corr. (mgal)	Reg. Corr. (mgal)	Boug. Anom. (mgal)	Ice Thkns (m)
3-9	424.9	-18.35	4.86	.09	-1.90	+0.49	-14.81	210
W. edge	399.6	00.00	0.00	0.00	0.00	0.00	0.00	
Line 4								
E. edge	527.6	0.00	0.00	0.00	0.00	0.00	0.00	
4-1	549.9	-16.62	4.26	-0.01	-2.93	0.30	15.00	212
4-2	549.5	-18.49	4.20	-0.09	-3.38	0.56	17.20	244
4-3	549.4	-18.75	4.20	-0.15	-3.56	0.79	17.47	247
4-4	554.8	-20.54	5.22	-0.19	-3.60	0.95	18.16	257
4-5	563.3	-21.51	6.85	-0.24	-3.57	1.13	17.34	246
4-6	573.9	-22.99	8.88	-0.28	-3.60	1.29	16.70	236
4-7	579.7	-24.14	10.00	-0.31	-3.62	1.39	16.68	236
4-9	586.6	-21.58	11.32	-0.39	-3.61	1.69	12.57	178
W. edge	574.1	0.36	8.88	-0.43	+2.32	1.99	0.00	
Line 8								
S. edge	965.7	0.00	0.00	0.00	0.00	0.00	0.00	
8-1	964.6	- 7.38	-0.21	-0.16	-0.70	-0.03	8.45	120
8-2	967.1	-14.95	+0.28	-0.32	-0.82	-0.06	15.81	224
8-3	968.2	-20.45	+0.44	-0.48	-0.81	-0.09	21.30	302
8-4	966.0	-24.31	0.00	-0.64	-1.11	-0.12	26.06	369
8-5	960.9	-26.25	-0.94	-0.80	-1.06	-0.15	29.05	411
8-6	954.1	-26.60	-2.20	-0.96	-1.11	-0.18	30.87	437
8-7	944.4	-24.75	-3.99	-1.12	-1.03	-0.21	30.89	437
8-8	934.3	-21.68	-5.74	-1.28	-1.04	-0.24	29.74	421
8-9	932.8	-19.07	-6.22	-1.41	-0.96	-0.27	27.66	392
8-10	935.2	-16.29	-5.77	-1.55	-0.92	-0.30	24.53	347
8-11	930.8	-12.38	-6.64	-1.64	-0.80	-0.33	21.46	304
8-12	924.0	- 6.72	-7.99	-1.74	-0.74	-0.37	17.19	243
8-13	918.7	+ 2.03	-9.05	-1.87	-0.39	-0.40	13.34	189
N. edge	917.7	+11.23	-9.21	-2.00	-0.30	-0.44	0.00	
Line 9								
SW. edge	1049.7	0.00	0.00	0.00	0.00	0.00	0.00	
9-1	1043.6	- 9.52	-1.17	-0.10	-0.83		11.62	165
9-2	1041.4	-13.74	-1.52	-0.21	-1.32		16.79	238
9-3	1047.2	-17.46	-0.41	-0.29	-2.06		20.22	286
9-4	1051.8	-19.62	+0.35	-0.36	-2.07		21.70	307
9-5	1054.4	-20.89	+0.88	-0.42	-2.17		22.60	320
9-6	1057.2	-21.69	+1.37	-0.48	-2.26		23.06	327
9-7	1060.3	-22.12	+2.00	-0.55	-2.32		22.99	326
9-8	1063.8	-21.94	+2.61	-0.61	-2.31		22.25	315
9-9	1065.4	-21.20	+3.23	-0.67	-2.34		20.98	297
9-10	1068.0	-19.92	+3.42	-0.74	-2.37		19.61	278
9-11	1069.7	-16.98	+3.67	-0.81	-2.31		16.43	233
9-12	1070.5	-15.55	+3.88	-0.87	-2.35		14.89	211

Station	Elev. (m)	Δg (mgal)	Comb. Boug. (mgal)	Lat. Corr. (mgal)	Terr Corr. (mgal)	Reg. Corr. (mgal)	Boug. Anom. (mgal)	Ice Thkns (m)
9-13	1068.8	-11.46	+3.36	-0.95	-2.20		11.25	159
9-14	1055.4	- 5.25	+1.12	-1.02	-2.26		7.41	105
NE end	1051.4	+ 2.90	+0.32	-1.09	-2.18		0.00	
Line 10								
SE end	1114.8	0.00	0.00	0.00	0.00	0.00	0.00	
10-1	1067.4	+ 4.49	-9.09	-0.08	-1.00	-0.15	5.53	78
10-2	1077.2	- 3.31	-7.21	-0.16	-1.17	-0.25	11.60	164
10-3	1083.9	- 9.72	-5.92	-0.24	-1.32	-0.40	16.80	238
10-4	1083.7	-13.35	-5.85	-0.31	-1.46	-0.50	20.47	290
10-5	1079.4	-13.62	-6.67	-0.39	-1.47	-0.60	21.55	305
10-6	1065.4	-14.88	-7.38	-0.47	-1.45	-0.70	23.48	332
10-7	1073.5	-14.22	-7.79	-0.55	-1.35	-0.80	23.01	326
10-8	1070.4	-13.07	-8.45	-0.63	-1.42	-0.90	22.77	322
10-9	1064.0	- 8.31	-9.59	-0.71	-1.25	-1.00	18.86	267
10-10	1057.8	- 3.63	-10.90	-0.79	-1.32	-1.10	15.54	220
10-11	1055.7	+ 0.73	-11.29	-0.87	-1.26	-1.20	11.49	163
10-12	1047.1	+ 6.29	-12.98	-0.95	-0.69	-1.30	7.03	100
NW end	1055.9	+11.66	-11.30	-1.05	-0.72	-1.41	0.00	
Line 11								
E. end	1060.9	+ 9.81	-7.22	-0.42	-1.16	-1.01	0.00	
11-1	1058.7	+ 2.55	-7.80	-0.34	-1.28	-0.90	7.77	110
11-2	1055.5	- 1.76	-8.39	-0.30	-1.55	-0.80	12.80	167
11-3	1054.9	- 5.65	-8.51	-0.27	-1.67	-0.70	16.80	238
11-4	1054.6	- 8.71	-8.58	-0.24	-1.83	-0.60	19.96	283
11-5	1055.0	-10.75	-8.48	-0.21	-1.88	-0.50	21.82	309
11-6	1059.8	-12,40	-7.59	-0.18	-1.85	-0.40	22.42	317
11-7	1067.4	-13.45	-6.15	-0.15	-1.95	-0.30	22.00	312
11-8	1072.9	-12.38	-4.64	-0.12	-1.88	-0.20	19.22	272
11-9	1072.0	- 8.72	-4.71	-0. 9	-1.84	-0.10	15.46	219
11-10	1071.7	- 3.96	-4.57	-0.06	-1.79	-0.05	10.43	147
W. end	1096.9	0.00	0.00	0.00	0.00	0.00	0.00	
Line 12								
NE end	1172.3	-10.91	+11.14	-1.41	+1.79	+0.61	0.00	
12-1	1141.3	-23.50	+ 5,19	-1.27	-0.52	+0.54	19.56	277
12-2	1132.1	-22.52	+ 3.43	-1.14	-0.82	+0.48	20.57	291
12-3	1131.6	-21.84	+ 3.31	-1.00	-0.95	+0.42	20.06	284
12-4	1128.6	-20.67	+ 2.91	-0.87	-0.98	+0.36	19.25	272
12-5	1120.5	-17.39	+ 1.32	-0.73	-1.05	+0.30	17.55	248
12-6	1110.5	-13.23	- 0.60	-0.59	-1.07	+0.24	15.25	216
12-7	1105.8	-10.13	- 1.57	-0.45	-0.82	+0.18	12.79	181
12-8	1103.9	- 7.22	- 1.95	-0.31	-0.66	+0.12	10.02	142
12-9	1101.3	- 3.91	- 2.46	-0.18	-0.37	+0.06	6.86	97

Station	Elev. (m)	Δg (mgal)	Comb. Boug. (mgal)	Lat. Corr. (mgal)	Terr. Corr. (mgal)	Reg Corr. (mgal)	Boug. Anom. (mgal)	Ice Thkns (m)
12-10	1097.4	+ 0.12	- 3.23	-0.09	-0.30	+0.03	3.47	50
SW end	1114.2	0.00	0.00	0.00	0.00	0.00	0.00	
<u>Line 13</u>								
W end	1138.9	0.00	0.00	0.00	0.00	0.00	0.00	
13-1	1142.0	- 7.50	+0.59	-0.06	-0.60	+0.10	7.47	105
13-2	1144.9	-12.21	+1.15	-0.11	-1.05	+0.20	12.02	170
13-3	1155.7	-18.31	+3.37	-0.15	-0.98	+0.40	15.67	220
13-4	1160.1	-22.16	+4.56	-0.19	-1.02	+0.60	18.21	254
13-5	1156.3	-23.26	+3.67	-0.24	-0.84	+0.80	19.87	281
13-6	1148.7	-22.75	+1.85	-0.29	-0.75	+1.00	20.94	296
13-7	1151.8	-21.87	+2.41	-0.35	-0.48	+1.20	19.09	270
13-8	1152.3	-19.14	+2.45	-0.40	+0.09	+1.40	15.60	220
E end	1172.3	- 9.31	+6.39	-0.47	+1.73	+1.66	0.00	

APPENDIX E

DATA FOR HEAT BALANCE STUDY

JULY 31, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TI E	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	3.06	3.28	.92	5.3315	2.22	.89	4.7846	676.15	-2.10	.000	3.6	3.2	.058
0030	3.33	3.61	.91	5.3994	3.61	.97	5.7554	676.15	-1.69	.000	3.6	3.2	.058
0100	3.33	3.33	.90	5.2362	2.22	.89	4.7846	676.15	.49	.000	1.8	1.9	.058
0130	2.50	2.50	1.00	5.4836	2.50	.86	4.7159	676.15	.22	.000	1.8	1.9	.058
0200	3.17	3.44	.91	5.3361	2.22	.97	5.2147	676.15	.46	.000	1.6	1.5	.058
0230	2.94	2.61	.94	5.1956	2.50	.86	4.7159	676.15	.73	.000	1.6	1.5	.058
0300	2.33	2.33	.98	5.3104	2.06	.94	4.9936	676.15	.59	.000	2.1	1.8	.058
0330	1.78	2.61	.99	5.4719	2.50	.86	4.7159	676.15	.36	.000	2.1	1.8	.058
0400	2.78	1.83	.96	5.0193	1.83	.97	5.0716	676.15	.39	.000	2.0	2.0	.058
0430	2.78	3.33	.92	5.3525	2.61	.90	4.9745	676.15	.60	.000	2.0	2.0	.058
0500	3.61	2.78	1.00	5.5931	1.83	.97	5.0716	676.15	.80	.000	1.9	1.7	.058
0530	2.22	2.33	.99	5.3646	2.06	.94	4.9936	676.15	1.11	.000	1.9	1.7	.058
0600	2.50	3.78	.96	5.7634	2.39	.93	5.0595	676.15	1.39	.000	1.8	1.8	.058
0630	2.89	3.39	.90	5.2568	2.22	.97	5.2147	676.40	3.34	.000	1.8	1.8	.058
0700	2.78	2.94	.91	5.1504	2.61	.89	4.9192	676.40	3.12	.000	2.0	1.7	.058
0730	3.17	3.33	.89	5.1780	2.11	.92	4.9068	676.40	3.57	.000	2.0	1.7	.058
0800	2.50	2.50	.91	4.9901	2.50	.86	4.7159	676.40	2.15	.000	2.1	1.8	.058
0830	2.50	3.06	.92	5.2482	2.50	.91	4.9901	676.40	2.14	.000	2.1	1.8	.058
0900	2.78	2.50	.91	4.9901	2.50	.86	4.7159	676.40	3.01	.000	2.2	2.0	.058
0930	3.06	2.78	.91	5.0897	3.06	.92	5.2482	676.40	4.14	.000	2.2	2.0	.058
1000	4.17	4.17	.83	5.1213	3.06	.92	5.2482	676.40	17.63	.000	1.0	1.1	.058
1030	4.72	3.06	.82	4.6778	3.06	.87	4.9630	676.15	8.32	.000	1.0	1.1	.058
1100	5.83	4.44	.83	5.2222	3.06	.87	4.9630	676.15	11.20	.000	1.4	1.3	.058
1130	5.28	3.89	.90	5.4457	2.50	.91	4.9901	676.15	10.99	.000	1.4	1.3	.058
1200	3.61	3.50	.98	5.7692	2.67	.86	4.7722	676.15	7.76	.000	2.1	1.6	.058
1230	3.94	2.78	.92	5.1457	2.28	.91	4.9116	675.89	7.10	.000	2.1	1.6	.058
1300	4.00	2.56	.69	4.8998	2.22	.92	4.9459	675.89	9.72	.000	2.0	2.0	.058
1330	3.78	3.11	.91	5.2117	2.50	.92	5.0449	675.89	8.67	.000	2.0	2.0	.058
1400	3.44	3.33	1.00	5.8180	2.67	.96	5.3271	675.89	6.51	.000	1.8	1.6	.058
1430	4.28	4.83	.95	6.1422	3.00	.88	5.0003	676.15	7.21	.000	1.8	1.6	.058
1500	3.78	4.11	.88	5.4087	2.50	.92	5.0449	676.15	6.02	.000	1.4	1.3	.058
1530	4.44	4.78	.96	6.1828	4.00	.95	5.7934	676.15	8.86	.025	1.4	1.3	.058
1600	5.06	4.72	.98	6.2871	4.33	.96	5.9932	676.15	7.91	.000	2.1	1.7	.058
1630	4.94	4.72	.96	6.1588	3.61	.98	5.8147	676.40	5.27	.000	2.1	1.7	.058
1700	4.44	3.78	.97	5.8235	2.89	.96	5.4120	676.40	5.72	.025	1.9	1.9	.058
1730	4.17	3.50	.96	5.6515	3.50	.98	5.7692	676.40	4.11	.000	1.9	1.9	.058
1800	3.28	3.22	.97	5.5992	2.78	.98	5.4813	676.40	2.16	.025	2.0	1.8	.058
1830	3.50	3.61	.96	5.6960	3.39	.98	5.7241	676.40	2.48	.013	2.0	1.8	.058
1900	4.06	4.94	.95	6.1901	3.94	.98	5.9530	676.40	4.45	.013	1.9	1.8	.058
1930	4.17	4.72	.96	6.1588	3.89	.98	5.9298	676.40	1.84	.000	1.9	1.8	.058
2000	3.33	3.61	.96	5.6960	3.33	.96	5.5853	676.40	1.78	.076	1.9	1.7	.058
2030	4.17	4.17	.96	5.9234	3.61	.96	5.6960	676.40	1.17	.000	1.9	1.7	.058
2100	4.17	5.00	.97	6.3450	4.72	.97	6.2230	676.40	.77	.000	1.7	1.7	.058
2130	4.44	5.28	.97	6.4691	2.78	.96	5.3694	676.40	.68	.000	1.7	1.7	.058
2200	3.89	4.17	1.00	6.1703	4.17	.96	5.9234	676.40	.61	.076	1.4	1.3	.058
2230	4.17	5.28	.93	6.2024	3.33	.88	5.1198	676.15	.57	.051	1.4	1.3	.058
2300	3.33	2.50	1.00	5.4836	3.61	.83	4.9247	676.15	.51	.013	2.0	1.6	.066
2330	3.33	5.00	.97	6.3450	5.00	.93	6.0834	676.15	.50	.000	2.0	1.6	.066

AUG. 1, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	3.39	3.61	.97	5.7554	3.11	.96	5.4980	676.15	.52	.025	1.7	1.8	.066
0030	2.89	3.50	.88	5.1805	3.00	.93	5.2844	676.15	.47	.064	1.7	1.8	.066
0100	4.44	5.94	.90	6.2869	4.83	.94	6.0776	676.15	.52	.025	1.8	1.5	.066
0130	3.78	3.33	.97	5.6434	2.89	.96	5.4120	676.15	.50	.025	1.8	1.5	.066
0200	3.39	3.39	1.00	5.8409	3.00	.95	5.3980	676.15	.42	.025	1.5	1.3	.066
0230	4.00	5.11	.96	6.3285	3.72	.98	5.8605	676.15	.50	.038	1.5	1.3	.066
0300	3.94	4.33	.98	6.1181	4.44	.92	5.7885	676.15	.38	.051	1.7	1.4	.066
0330	4.22	5.11	.94	6.1966	4.00	1.00	6.0983	676.15	.46	.051	1.7	1.4	.066
0400	3.89	3.61	.98	5.8147	3.61	.97	5.7554	676.15	.50	.025	2.4	2.1	.066
0430	3.44	4.33	.90	5.6186	5.00	.90	5.8871	676.15	.48	.013	2.4	2.1	.066
0500	2.67	2.83	.98	5.5030	2.61	.95	5.2508	676.15	.61	.000	2.4	2.3	.066
0530	2.50	2.22	.95	5.1072	2.50	.94	5.1546	676.15	1.22	.013	2.4	2.3	.066
0600	2.61	2.06	.98	5.2061	2.00	.96	5.0796	676.15	1.49	.000	1.3	1.3	.066
0630	2.67	3.61	.98	5.8147	1.83	.96	5.0193	675.89	1.50	.025	1.3	1.3	.066
0700	2.33	2.50	1.00	5.4836	1.94	.95	5.0067	675.89	2.24	.000	1.4	1.3	.066
0730	2.22	3.06	.98	5.5905	2.11	.96	5.1201	675.89	3.00	.013	1.4	1.3	.066
0800	2.22	2.50	.91	4.9901	1.39	1.00	5.0643	675.89	4.32	.038	1.5	1.3	.066
0830	3.61	4.17	1.00	6.1703	1.94	.96	5.0594	676.15	4.54	.025	1.5	1.3	.066
0900	2.78	3.89	.92	5.5667	2.50	.96	5.2643	676.15	5.90	.038	1.2	1.2	.066
0930	2.50	2.50	1.00	5.4836	2.22	.91	4.8922	676.15	6.64	.013	1.2	1.2	.066
1000	3.06	5.00	.93	6.0834	2.22	.96	5.1610	676.15	5.52	.013	1.3	1.3	.066
1030	3.33	4.17	.92	5.6766	2.50	.96	5.2643	676.40	6.34	.013	1.3	1.3	.066
1100	3.89	4.44	.96	6.0401	3.06	.96	5.4764	676.40	8.53	.000	1.0	1.0	.066
1130	5.28	4.72	.96	6.1588	4.17	.96	5.9234	676.40	7.74	.025	1.0	1.0	.066
1200	6.22	4.72	.98	6.2871	3.50	.94	5.5338	676.40	8.03	.025	1.0	1.0	.066
1230	4.17	5.17	.98	6.4854	2.78	1.00	5.5931	676.66	10.66	.038	1.0	1.0	.066
1300	5.83	5.06	.97	6.3697	4.83	.84	5.4310	676.66	8.50	.038	2.6	2.0	.066
1330	4.67	4.50	.98	6.1900	4.11	.96	5.9004	676.66	6.11	.013	2.6	2.0	.066
1400	4.50	4.89	.99	6.4258	3.72	.95	5.6811	676.66	4.97	.013	3.0	2.6	.066
1430	6.28	7.00	.94	7.0623	5.28	.85	5.6688	676.91	7.29	.038	3.0	2.6	.066
1500	5.78	6.50	.98	7.1137	4.78	.98	6.3116	676.91	6.37	.013	2.5	2.6	.066
1530	5.56	6.17	.92	6.5262	5.28	.95	6.3358	676.91	3.56	.051	2.5	2.6	.066
1600	4.72	4.61	.98	6.2384	5.28	.97	6.4691	676.91	4.02	.008	.9	.8	.066
1630	5.50	5.11	.97	6.3944	4.17	.95	5.8617	676.91	4.84	.005	.9	.8	.066
1700	4.67	3.50	1.00	5.8870	5.11	.95	6.2626	676.91	4.70	.025	1.4	1.3	.066
1730	5.00	5.00	.98	6.4104	4.17	.94	5.8000	676.91	4.08	.051	1.4	1.3	.066
1800	3.61	6.11	.93	6.5718	2.22	.96	5.1610	676.91	1.97	.038	2.1	1.9	.066
1830	3.11	4.28	.99	6.1564	2.94	.98	5.5466	677.16	1.83	.038	2.1	1.9	.066
1900	4.28	4.22	.99	6.1325	2.94	.98	5.5466	677.16	3.05	.000	2.3	1.9	.066
1930	3.94	6.11	.93	6.5718	3.61	1.00	5.9334	677.16	1.98	.025	2.3	1.9	.066
2000	4.72	5.56	.97	6.5954	4.72	.92	5.9022	677.16	1.47	.051	2.5	2.3	.066
2030	5.56	5.83	1.00	6.9318	3.89	.96	5.8088	677.42	1.27	.038	2.5	2.3	.066
2100	4.72	5.28	.93	6.2024	4.44	.96	6.0401	677.42	1.01	.064	2.3	2.1	.066
2130	4.72	5.00	.97	6.3450	5.56	.97	6.5954	677.42	.67	.051	2.3	2.1	.066
2200	5.28	6.39	.93	6.6992	5.56	.93	6.3234	677.42	.61	.051	1.9	1.8	.066
2230	6.39	6.67	1.00	7.3428	5.28	.97	6.4691	677.67	.60	.025	1.9	1.8	.066
2300	5.00	6.39	.93	6.6992	4.17	.92	5.6766	677.67	.65	.076	2.3	1.9	.066
2330	5.83	6.39	1.00	7.2035	6.94	.93	6.9606	677.67	.57	.038	2.3	1.9	.066

AUG. 2, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	4.94	4.78	.98	6.3116	4.00	.94	5.7324	677.67	.66	.094	2.2	2.1	.075
0030	5.50	5.56	1.00	6.7994	4.61	1.00	6.3657	677.67	.61	.046	2.7	2.4	.075
0100	5.11	6.44	.96	6.9419	5.50	.93	6.2991	677.67	.48	.025	2.7	2.4	.075
0130	4.39	4.61	1.00	6.3657	4.28	.95	5.9077	677.67	.51	.051	2.5	2.4	.075
0200	5.11	5.33	1.00	6.6951	3.94	.94	5.7101	677.67	.57	.051	2.5	2.4	.075
0230	4.61	5.44	.96	6.4772	3.89	.96	5.8088	677.67	.59	.000	1.6	1.5	.075
0300	3.83	3.67	1.00	5.9567	3.44	.95	5.5707	677.67	.60	.025	1.6	1.5	.075
0330	3.33	3.72	.88	5.2625	3.67	.88	5.2419	677.67	.49	.025	2.4	2.2	.075
0400	2.89	3.39	1.00	5.8409	2.33	.99	5.3646	677.67	.48	.025	2.4	2.2	.075
0430	2.78	3.67	.94	5.5993	2.22	.96	5.1610	677.67	.68	.038	1.6	1.5	.075
0500	3.89	4.56	.99	6.2776	3.61	.96	5.6960	677.67	.69	.064	1.6	1.5	.075
0530	3.33	4.61	.98	6.2384	3.00	.97	5.5117	677.67	.74	.038	2.1	1.2	.075
0600	3.06	4.33	.90	5.6166	2.17	.98	5.2476	677.67	.88	.102	2.1	1.2	.075
0630	3.78	3.17	.98	5.6347	4.89	.98	6.3609	677.67	1.62	.051	2.0	1.4	.075
0700	3.50	3.11	.98	5.6126	3.33	.92	5.3525	677.67	1.95	.038	2.0	1.4	.075
0730	3.78	4.33	.96	5.9932	2.33	.98	5.3104	677.67	3.82	.025	2.2	1.8	.075
0800	3.89	3.06	1.00	5.7046	4.17	1.00	6.1703	677.67	4.55	.013	2.2	1.8	.075
0830	4.72	7.50	.93	7.2309	6.39	.85	6.1229	677.67	5.87	.000	2.3	1.8	.075
0900	6.39	6.67	.97	7.1225	5.00	.80	5.2330	677.67	7.99	.000	2.3	1.8	.075
0930	6.39	6.39	.97	6.9874	5.28	.93	6.2024	677.67	6.89	.000	2.0	1.7	.075
1000	4.44	4.72	1.00	6.4155	3.61	.92	5.4587	677.67	7.81	.000	2.0	1.7	.075
1030	5.00	5.28	.96	6.4024	3.33	.96	5.5853	677.67	7.19	.000	2.7	1.8	.075
1100	5.28	5.56	.93	6.3234	4.44	.92	5.7885	677.67	11.96	.000	2.7	1.8	.075
1130	4.44	3.61	.92	5.4587	3.06	.92	5.2482	677.67	9.07	.000	2.2	1.8	.075
1200	5.28	5.28	.96	6.4024	6.00	.79	5.5397	677.67	6.94	.000	2.2	1.8	.075
1230	5.33	5.94	.97	6.7758	4.39	.96	6.0166	677.93	11.75	.000	2.6	1.8	.075
1300	5.83	4.44	.93	5.8514	4.39	.97	6.0793	677.93	11.34	.000	2.6	1.8	.075
1330	6.00	5.39	1.00	6.7210	4.28	.96	5.9699	677.93	15.71	.000	2.7	2.2	.075
1400	7.78	4.44	.97	6.1030	4.33	.98	6.1181	677.93	15.24	.000	2.7	2.2	.075
1430	5.28	3.22	.97	5.5992	2.94	1.00	5.6598	678.18	13.92	.000	3.3	2.4	.075
1500	5.56	4.44	1.00	6.2918	4.17	.84	5.1830	678.18	14.34	.000	3.3	2.4	.075
1530	4.83	4.33	.98	6.1181	3.11	.97	5.5553	678.18	8.40	.000	2.9	1.9	.075
1600	4.61	4.28	.91	5.6589	3.89	.88	5.3247	678.18	10.82	.000	2.9	1.9	.075
1630	5.06	4.89	.86	5.5820	3.89	.87	5.2642	678.18	12.11	.000	1.8	1.7	.075
1700	6.00	5.39	.83	5.5784	4.33	.85	5.3065	678.18	14.66	.000	1.8	1.7	.075
1730	5.56	4.67	.95	6.0710	2.89	.89	5.0173	678.18	13.73	.000	2.5	1.6	.075
1800	4.67	3.72	.96	5.7409	2.44	.95	5.1888	678.18	6.52	.000	2.5	1.6	.075
1830	2.89	3.72	.96	5.7409	3.22	.95	5.4838	678.18	3.60	.025	2.3	2.1	.075
1900	5.11	3.50	.96	5.6515	3.06	.98	5.5905	678.18	3.57	.000	2.3	2.1	.075
1930	3.50	4.17	.92	5.6766	3.33	.95	5.5271	678.18	2.37	.000	2.4	2.2	.075
2000	2.67	3.33	.92	5.3525	3.06	.92	5.2482	678.18	2.25	.000	2.4	2.2	.075
2030	3.33	3.89	.92	5.5667	2.50	.91	4.9901	677.93	1.45	.000	2.1	1.8	.075
2100	3.33	4.17	.92	5.6766	2.78	.96	5.3694	677.93	1.13	.000	2.1	1.8	.075
2130	3.06	3.06	.96	5.4764	2.78	.92	5.1457	677.93	.82	.000	2.8	2.6	.075
2200	3.06	3.33	.92	5.3525	3.06	.92	5.2482	677.93	.72	.000	2.8	2.6	.075
2230	3.33	3.89	.92	5.5667	3.06	.94	5.3623	677.93	.66	.000	2.0	1.4	.075
2300	2.78	4.44	.87	5.4739	4.44	.87	5.4739	677.93	-.07	.000	2.0	1.4	.075
2330	3.61	4.44	.67	5.4739	3.89	.96	5.8088	677.93	-.28	.000	1.7	1.4	.075

AUG. 3, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	3.33	5.00	.93	6.0834	1.94	.96	5.0594	677.93	-.59	.000	1.7	1.4	.071
0030	4.22	5.83	.90	6.2386	4.61	.89	5.6655	677.67	-1.03	.000	2.1	1.8	.071
0100	3.17	4.39	.91	5.7033	2.39	.95	5.1683	677.67	.55	.000	2.1	1.8	.071
0130	2.78	3.33	.90	5.2362	2.61	.90	4.9745	677.67	.63	.000	1.7	1.5	.071
0200	3.33	4.50	.91	5.7479	2.28	.92	4.9656	677.67	-.60	.000	1.7	1.5	.071
0230	3.22	4.33	.93	5.8059	3.00	.81	4.6025	677.67	-.67	.000	1.9	1.6	.071
0300	2.67	3.89	.97	5.8693	1.72	.97	5.0314	677.67	-.75	.000	1.9	1.6	.071
0330	2.78	5.06	.96	6.3040	3.06	.96	5.4764	677.67	-1.22	.000	2.1	1.6	.071
0400	2.61	2.78	.90	5.0338	2.22	.94	5.0534	677.67	-1.00	.000	2.1	1.6	.071
0430	2.22	5.06	.84	5.5160	2.50	.94	5.1546	677.42	-.82	.000	2.1	1.6	.071
0500	2.22	4.39	.91	5.7033	1.89	.95	4.9869	677.42	-.69	.000	2.1	1.6	.071
0530	2.61	5.72	.81	5.5716	2.78	.75	4.1948	677.42	-.24	.000	2.4	2.1	.071
0600	3.06	4.72	.83	5.3248	3.33	.88	5.1198	677.42	.02	.000	2.4	2.1	.071
0630	3.06	3.61	.83	4.9247	2.50	.86	4.7159	677.16	1.82	.000	2.1	1.9	.071
0700	4.44	4.17	.83	5.1213	3.33	.88	5.1198	677.16	5.36	.000	2.1	1.9	.071
0730	4.44	5.28	.76	5.0686	2.50	.91	4.9901	677.16	7.87	.000	2.1	1.9	.071
0800	5.56	6.11	.78	5.5119	3.06	.82	4.6778	677.16	10.63	.000	2.1	1.9	.071
0830	5.56	4.44	.83	5.2222	3.06	.82	4.6778	676.91	12.53	.000	2.3	2.2	.071
0900	5.56	5.83	.74	5.1295	3.06	.82	4.6778	676.91	14.60	.000	2.3	2.2	.071
0930	5.56	4.72	.75	4.8116	3.06	.82	4.6778	676.91	15.95	.000	2.1	1.8	.071
1000	5.56	5.56	.73	4.9636	3.61	.75	4.4500	676.91	17.87	.000	2.1	1.8	.071
1030	5.56	5.83	.69	4.7829	3.61	.83	4.9247	676.66	20.57	.000	2.4	2.1	.071
1100	6.67	6.67	.71	5.2134	3.33	.83	4.8289	676.66	21.60	.000	2.4	2.1	.071
1130	6.67	5.28	.76	5.0686	3.61	.79	4.6874	676.66	22.15	.000	2.3	2.0	.071
1200	6.28	5.44	.68	4.5880	3.89	.78	4.7196	676.66	22.00	.000	2.3	2.0	.071
1230	6.72	5.78	.74	5.1098	3.67	.79	4.7058	676.66	17.73	.000	2.2	2.0	.071
1300	5.00	6.11	.67	4.7345	3.61	.79	4.6874	676.66	24.54	.000	2.2	2.0	.071
1330	6.94	5.72	.73	5.0214	4.33	.77	4.8071	676.66	24.19	.000	2.6	2.4	.071
1400	6.56	5.44	.68	4.5880	3.56	.79	4.6690	676.66	22.23	.000	2.6	2.4	.071
1430	5.56	5.56	.77	5.2355	4.83	.75	4.8491	676.40	21,52	.000	2.5	2.3	.071
1500	7.22	6.56	.67	4.8821	3.78	.78	4.6828	676.40	20.36	.000	2.5	2.3	.071
1530	6.61	4.50	.83	5.2426	4.44	.77	4.8447	676.40	19.15	.000	2.4	2.3	.071
1600	7.22	5.22	.76	5.0490	3.89	.83	5.0222	676.40	17.78	.000	2.4	2.3	.071
1630	6.61	5.28	.77	5.1353	3.50	.86	5.0628	676.40	16.01	.000	2.7	2.6	.071
1700	6.67	3.89	.86	5.2037	3.33	.83	4.8289	676.40	14.02	.000	2.7	2.6	.071
1730	6.61	4.22	.82	5.0794	3.67	.82	4.8845	676.40	11.98	.000	2.4	2.1	.071
1800	6.39	5.00	.79	5.1676	3.89	.83	5.0222	676.40	9.14	.000	2.4	2.1	.071
1830	7.22	6.67	.78	5.7274	3.33	.88	5.1198	676.15	7.37	.000	2.7	2.5	.071
1900	7.22	5.28	.84	5.6021	3.89	.83	5.0222	676.15	5.08	.000	2.7	2.5	.071
1930	7.22	5.00	.84	5.4946	4.17	.83	5.1213	676.15	3.06	.000	2.4	2.2	.071
2000	6.67	5.28	.84	5.6021	3.89	.83	5.0222	676.15	.73	.000	2.4	2.2	.071
2030	4.44	4.72	.83	5.3248	3.61	.88	5.2214	676.40	-1.46	.000	2.3	2.0	.071
2100	3.61	3.89	.87	5.2642	3.33	.88	5.1198	676.40	-1.81	.000	2.3	2.0	.071
2130	3.33	4.17	.83	5.1213	2.78	.92	5.1457	676.40	-2.13	.000	2.5	2.3	.071
2200	3.33	5.83	.83	5.7534	2.78	.92	5.1457	676.40	-2.21	.000	2.5	2.3	.071
2230	3.33	4.44	.83	5.2222	2.78	.87	4.8660	676.66	-2.29	.000	2.3	2.0	.071
2300	3.06	3.06	.92	5.2482	2.78	.87	4.8660	676.66	-2.25	.000	2.3	2.0	.071
2330	3.06	4.72	.88	5.6456	2.78	.87	4.8660	676.66	-2.28	.000	2.4	2.1	.071

AUGUST 26, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TI.E	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	3.61	4.72	.75	4.8116	3.61	.99	5.8740	668.02	.58	.000	2.0	1.7	.049
0030	2.61	3.89	.92	5.5667	3.67	.96	5.7184	668.02	.71	.127	2.0	1.7	.049
0100	4.33	4.17	.99	6.1086	4.22	.94	5.8227	668.02	.55	.051	2.0	1.7	.049
0130	4.33	5.00	.93	6.0834	4.22	.96	5.9466	668.02	.27	.000	1.1	1.0	.049
0200	3.22	4.17	.85	5.2447	3.44	.91	5.3361	668.02	.33	.000	1.1	1.0	.049
0230	3.33	3.78	.92	5.5233	2.61	.97	5.3614	668.02	.61	.000	1.6	1.3	.049
0300	4.00	4.72	.94	6.0305	4.56	.91	5.7703	668.02	.50	.102	1.6	1.3	.049
0330	3.89	3.72	.98	5.8605	3.00	.99	5.6253	668.02	.58	.127	1.8	1.3	.049
0400	4.17	4.72	.92	5.9022	3.61	.92	5.4587	668.02	.49	.178	1.8	1.3	.049
0430	3.61	4.17	.96	5.9234	4.72	.95	6.0947	668.02	.41	.051	1.6	1.5	.049
0500	3.89	3.89	.96	5.8088	4.17	.92	5.6766	668.02	.48	.102	1.6	1.5	.049
0530	3.61	3.33	1.00	5.8180	3.28	.96	5.5633	642.62	.49	.076	1.5	1.2	.049
0600	3.89	4.17	.92	5.6766	3.61	1.00	5.9334	668.02	.56	.076	1.5	1.2	.049
0630	3.33	3.33	1.00	5.8180	3.06	.96	5.4764	668.02	.62	.076	1.4	1.1	.049
0700	3.33	3.33	.96	5.5853	3.06	.96	5.4764	668.02	.74	.127	1.4	1.1	.049
0730	3.89	3.06	.96	5.4764	3.89	.79	4.7801	668.02	1.67	.076	1.6	1.5	.049
0800	3.56	3.17	.96	5.5197	2.44	1.00	5.4619	668.02	1.40	.076	1.6	1.5	.049
0830	3.00	3.06	1.00	5.7046	2.78	.99	5.5372	668.27	1.63	.064	1.3	1.2	.049
0900	3.78	3.78	.98	5.8835	2.78	1.00	5.5931	668.27	2.29	.038	1.3	1.2	.049
0930	3.33	4.33	.94	5.8064	2.94	.94	5.3202	668.27	2.62	.089	1.4	1.2	.049
1000	4.00	4.44	.96	6.0401	3.06	.93	5.3053	668.27	3.06	.013	1.4	1.2	.049
1030	3.67	4.33	.94	5.8684	4.44	.84	5.2851	668.53	2.67	.000	1.0	.9	.049
1100	3.78	4.33	.95	5.9308	3.22	.92	5.3106	668.53	3.57	.013	1.0	.9	.049
1130	4.17	4.28	.93	5.7833	3.56	.93	5.4964	668.53	3.37	.013	1.9	1.4	.049
1200	3.89	3.67	.74	4.4080	3.06	.87	4.9630	668.53	3.57	.076	1.9	1.4	.049
1230	3.39	4.39	.91	5.7033	2.67	.93	5.1607	669.04	4.51	.076	2.0	1.7	.049
1300	4.22	4.33	.92	5.7435	3.11	.99	5.6698	669.04	4.88	.076	2.0	1.7	.049
1330	4.28	4.89	.93	6.0363	3.06	.97	5.5334	669.04	4.14	.013	2.5	2.4	.049
1400	4.33	3.89	.96	5.8088	3.83	.94	5.6655	669.04	5.81	.038	2.5	2.4	.049
1430	4.67	5.00	.91	5.9525	3.78	.98	5.8835	669.29	4.73	.000	2.1	2.0	.049
1500	3.67	4.28	.91	5.6589	3.61	.99	5.8740	669.29	4.12	.089	2.1	2.0	.049
1530	3.28	3.78	.93	5.5833	2.33	.98	5.3104	669.29	2.47	.013	2.2	1.9	.049
1600	3.61	3.22	.96	5.5415	2.50	1.00	5.4836	669.29	2.50	.064	2.2	1.9	.049
1630	4.17	4.72	.92	5.9022	3.61	.96	5.6960	669.54	2.45	.013	2.2	2.1	.049
1700	3.89	4.17	.92	5.6766	3.61	.96	5.6960	669.54	2.17	.038	2.2	2.1	.049
1730	4.17	4.72	.92	5.9022	3.61	.96	5.6960	669.54	1.54	.064	1.8	1.6	.049
1800	4.44	4.72	.96	6.1588	4.17	.96	5.9234	669.54	1.55	.025	1.8	1.6	.049
1830	4.17	3.89	1.00	6.0508	3.06	1.00	5.7046	669.80	1.04	.076	2.3	1.9	.049
1900	4.17	4.44	.96	6.0401	3.61	.96	5.6960	669.80	1.02	.076	2.3	1.9	.049
1930	4.17	4.17	.96	5.9234	3.06	.95	5.4193	669.80	.75	.013	1.9	1.8	.049
2000	4.17	4.44	.96	6.0401	3.89	.96	5.8088	669.80	.65	.013	1.9	1.8	.049
2030	3.94	4.44	.97	6.1030	3.11	.98	5.6126	669.80	.61	.076	1.9	1.6	.049
2100	4.06	4.44	.95	5.9772	3.61	.99	5.8740	670.05	.59	.089	1.9	1.6	.049
2130	3.94	4.28	.95	5.9077	3.33	1.00	5.8180	670.05	.57	.051	1.6	1.5	.049
2200	3.89	4.17	1.00	6.1703	2.67	1.00	5.5491	670.31	.51	.064	1.6	1.5	.049
2230	3.67	4.17	.97	5.9851	3.28	.96	5.5633	670.31	.58	.038	1.3	1.2	.049
2300	3.89	4.44	.96	6.0401	3.33	.96	5.5853	670.31	.48	.038	1.3	1.2	.049
2330	4.22	4.89	.95	6.1661	4.44	.96	6.0401	670.56	.51	.025	1.5	1.4	.049

AUGUST 27, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	4.61	4.72	.96	6.1588	2.72	.95	5.2925	670.56	.50	.013	1.5	1.4	.064
0030	3.83	4.06	.93	5.6937	2.50	.97	5.3191	671.07	.56	.076	1.7	1.5	.064
0100	2.78	3.61	.95	5.6367	1.89	.96	5.0393	671.07	.48	.000	1.7	1.5	.064
0130	2.56	3.11	.95	5.4407	2.56	.99	5.4503	671.07	.48	.076	1.5	1.4	.064
0200	3.33	3.39	.99	5.7825	2.78	.99	5.5372	671.07	.50	.051	1.5	1.4	.064
0230	4.28	4.89	.92	5.9714	3.89	.84	5.0827	671.58	.54	.000	1.2	1.1	.064
0300	4.61	5.22	.94	6.2448	4.39	.98	6.1420	671.58	.55	.000	1.2	1.1	.064
0330	3.94	4.22	.92	5.6988	4.00	.91	5.5495	671.58	.48	.013	1.3	1.2	.064
0400	3.89	5.11	.92	6.0648	3.22	.99	5.7147	671.58	.45	.013	1.3	1.2	.064
0430	3.33	4.44	.83	5.2222	2.78	.95	5.3135	671.83	.34	.000	1.4	1.2	.064
0500	3.06	3.89	.92	5.5667	3.06	.91	5.1912	671.83	.45	.000	1.4	1.2	.064
0530	2.78	3.61	.92	5.4587	2.78	.95	5.3135	671.83	.41	.000	1.7	1.5	.064
0600	2.22	2.50	.95	5.2094	2.22	.95	5.1072	671.83	.53	.000	1.7	1.5	.064
0630	2.50	3.06	.91	5.1912	2.50	.95	5.2094	672.59	1.08	.000	1.4	1.3	.064
0700	2.22	3.06	.91	5.1912	2.50	.95	5.2094	672.59	1.47	.000	1.4	1.3	.064
0730	2.22	2.22	.95	5.1072	2.17	.95	5.0870	672.59	1.97	.013	1.4	1.3	.064
0800	2.22	2.78	.95	5.3135	2.72	.91	5.0697	672.59	3.92	.000	1.4	1.3	.064
0830	3.28	3.50	.88	5.1805	2.94	.89	5.0372	672.85	6.00	.000	1.6	1.2	.064
900	3.39	3.78	.85	5.1030	3.22	.87	5.0220	672.85	6.71	.000	1.6	1.2	.064
930	5.17	5.00	.86	5.6255	4.17	.84	5.1830	672.85	16.60	.000	1.4	1.2	.064
1000	6.67	4.67	.88	5.6237	3.17	.89	5.1172	672.85	10.98	.000	1.4	1.2	.064
1030	4.44	2.89	.95	5.3556	2.22	.91	4.8922	673.10	13.67	.000	1.8	1.7	.064
1100	5.22	4.61	.88	5.6018	2.50	.91	4.9901	673.10	18.22	.000	1.8	1.7	.064
1130	6.56	5.28	.82	5.4688	2.22	.91	4.8922	673.10	17.72	.000	1.9	1.7	.064
1200	5.83	4.33	.79	4.9319	2.11	.87	4.6401	673.10	16.01	.000	1.9	1.7	.064
1230	5.17	4.56	.94	5.9605	3.06	.94	5.3623	673.61	15.64	.000	2.1	1.8	.064
1300	4.44	2.72	.92	5.1254	2.22	.91	4.8922	673.61	12.56	.000	2.1	1.6	.064
1330	4.94	3.56	1.00	5.9101	3.28	.96	5.5633	673.61	17.20	.000	1.7	1.6	.064
1400	6.11	4.33	.86	5.3689	2.61	.93	5.1403	673.61	13.01	.000	1.7	1.6	.064
1430	5.67	3.50	.84	4.9451	2.72	.89	4.9583	673.61	13.56	.000	1.4	1.3	.064
1500	5.00	3.22	.94	5.4260	2.89	.87	4.9046	673.61	13.73	.000	1.4	1.3	.064
1530	4.94	4.94	.82	5.3430	3.67	.91	5.4206	673.61	19.80	.000	1.9	1.7	.064
1600	5.22	4.17	.89	5.4915	3.89	.83	5.0222	673.61	10.90	.000	1.9	1.7	.064
1630	4.72	4.17	.83	5.1213	3.89	.83	5.0222	673.35	8.18	.000	1.8	1.7	.064
1700	4.44	3.06	.87	4.9630	1.94	.91	4.7959	673.35	5.20	.000	1.8	1.7	.064
1730	4.17	5.83	.73	5.0602	3.89	.83	5.0222	673.35	4.68	.000	2.0	1.7	.064
1800	4.17	3.89	.79	4.7801	2.78	.87	4.8660	673.35	3.83	.000	2.0	1.7	.064
1830	4.72	3.61	.83	4.9247	3.56	.75	4.4326	673.10	1.57	.000	1.3	1.2	.064
1900	4.44	5.00	.72	4.7097	3.61	.79	4.6874	673.10	.63	.000	1.3	1.2	.064
1930	3.33	3.61	.79	4.6874	3.89	.79	4.7801	673.10	-.64	.000	1.6	1.4	.064
2000	4.17	5.83	.81	5.6148	3.33	.79	4.5962	673.10	-1.81	.000	1.6	1.4	.064
2030	4.44	9.78	.49	4.4460	7.56	.58	4.5267	673.10	-2.52	.000	1.7	1.6	.064
2100	4.33	6.11	.63	4.4519	3.61	.75	4.4500	673.10	-2.87	.000	1.7	1.6	.064
2130	4.61	4.67	.73	4.6651	4.44	.70	4.4043	673.10	-3.01	.000	1.6	1.5	.064
2200	4.17	4.44	.70	4.4043	2.33	.80	4.3350	673.10	-3.03	.000	1.6	1.5	.064
2230	3.28	4.61	.70	4.4560	3.61	.68	4.0347	673.35	-2.90	.000	1.2	1.1	.064
2300	3.50	4.72	.79	5.0682	2.67	.75	4.1618	673.35	-2.87	.000	1.2	1.1	.064
2330	2.83	4.33	.65	4.0579	3.72	.67	4.0067	673.35	-2.80	.000	.8	.7	.064

AUGUST 28, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	3.61	3.67	.74	4.4080	3.06	.75	4.2784	673.35	-2.50	.000	.8	.7	.059
0030	3.61	4.06	.70	4.2856	3.06	.73	4.1643	673.86	-2.50	.000	1.0	.9	.059
0100	5.28	5.78	.85	5.8694	3.61	.75	4.4500	673.86	-2.72	.000	1.0	.9	.059
0130	3.89	4.67	.72	4.6012	3.89	.70	4.2356	673.86	-2.72	.000	1.1	1.0	.059
0200	4.89	6.94	.59	4.4158	5.72	.65	4.4711	673.86	-2.61	.000	1.1	1.0	.059
0230	4.44	6.33	.70	5.0231	3.22	.77	4.4447	673.86	-2.39	.000	1.5	1.2	.059
0300	5.44	6.94	.56	4.1913	5.83	.64	4.4364	673.86	-1.85	.000	1.5	1.2	.059
0330	4.83	6.67	.71	5.2134	2.61	.84	4.6428	673.86	-1.58	.000	1.2	1.1	.059
0400	5.67	7.94	.75	6.0111	5.28	.72	4.8018	673.86	-1.05	.000	1.2	1.1	.059
0430	7.22	9.17	.53	4.6151	6.39	.66	4.7543	673.86	-.92	.000	2.0	1.8	.059
0500	7.22	5.83	.65	4.5057	5.56	.69	4.6916	673.86	-.87	.000	2.0	1.8	.059
0530	5.00	5.00	.72	4.7097	3.61	.75	4.4500	673.86	-1.01	.000	1.5	1.4	.059
0600	7.50	9.44	.60	5.3234	8.89	.59	5.0420	673.86	-.39	.000	1.5	1.4	.059
0630	7.50	9.72	.54	4.8814	7.22	.65	4.9586	674.12	.02	.000	1.0	.9	.059
0700	8.06	8.61	.65	5.4512	7.50	.66	5.1316	674.12	1.29	.000	1.0	.9	.059
0730	6.39	6.67	.67	4.9197	4.72	.75	4.8116	674.12	2.69	.000	2.2	1.8	.059
0800	5.56	6.67	.63	4.6260	5.83	.70	4.8523	674.12	3.62	.000	2.2	1.8	.059
0830	6.44	8.22	.63	5.1457	4.94	.65	4.2353	674.62	3.91	.000	1.0	.9	.059
0900	7.33	7.78	.68	5.3884	4.17	.78	4.8128	674.62	4.89	.000	1.0	.9	.059
0930	6.67	6.72	.72	5.3071	5.00	.70	4.5789	674.62	4.40	.000	2.0	1.8	.059
1000	7.56	4.89	.77	4.9978	3.33	.83	4.8289	674.62	7.54	.000	2.0	1.8	.059
1030	7.89	7.22	.73	5.5689	4.72	.74	4.7474	674.88	10.72	.000	2.2	1.8	.059
1100	6.61	7.22	.64	4.8823	3.56	.80	4.7281	674.88	9.53	.000	2.2	1.8	.059
1130	6.89	8.17	.60	4.8822	6.89	.67	4.9955	674.88	11.23	.000	1.7	1.6	.059
1200	7.89	5.67	.69	4.7279	4.83	.74	4.7845	674.88	11.59	.000	1.7	1.6	.059
1230	6.61	5.72	.74	5.0901	4.56	.81	5.1362	674.88	15.24	.000	2.5	2.1	.059
1300	6.17	5.17	.82	5.4266	4.83	.76	4.9138	674.88	13.90	.000	2.5	2.1	.059
1330	7.67	7.67	.69	5.4263	5.50	.63	4.2671	674.88	22.23	.000	1.5	1.4	.059
1400	9.28	9.33	.65	5.7240	7.39	.76	5.8643	674.88	12.24	.000	1.5	1.4	.059
1430	10.11	10.83	.61	5.9398	9.83	.70	6.3752	674.88	12.98	.000	1.2	1.0	.059
1500	8.78	5.50	.77	5.2153	4.06	.85	5.2039	674.88	12.22	.000	1.2	1.0	.059
1530	6.22	6.06	.74	5.2091	4.69	.84	5.4522	674.88	10.75	.000	1.5	1.3	.059
1600	5.72	4.89	.81	5.2574	4.22	.84	5.2033	674.88	8.20	.000	1.5	1.3	.059
1630	5.56	5.83	.74	5.1295	5.28	.76	5.0686	674.88	9.75	.000	1.8	1.6	.059
1700	6.11	6.39	.78	5.6187	4.72	.83	5.3248	674.88	6.16	.000	1.8	1.6	.059
1730	6.11	7.22	.72	5.4926	5.00	.84	5.4946	674.88	5.21	.000	2.2	2.1	.059
1800	6.67	6.33	.68	5.5962	6.11	.70	4.9465	674.88	4.15	.000	2.2	2.1	.059
1830	5.83	6.67	.71	5.2134	5.00	.76	4.9713	674.88	2.94	.000	1.5	1.4	.059
1900	5.56	7.78	.65	5.1507	4.72	.83	5.3248	674.88	1.92	.000	1.5	1.4	.059
1930	5.28	5.83	.77	5.3375	5.00	.76	4.9713	674.88	1.42	.000	1.8	1.7	.059
2000	6.39	7.22	.72	5.4926	5.28	.92	6.1357	674.88	.70	.000	1.8	1.7	.059
2030	4.94	5.44	.76	5.1278	4.50	.77	4.8636	674.88	.31	.000	1.5	1.4	.059
2100	6.06	7.61	.73	5.7191	3.69	.86	5.2037	674.88	.57	.000	1.5	1.4	.059
2130	6.28	5.72	.84	5.7780	4.50	.86	5.4321	674.88	.88	.000	2.0	1.8	.059
2200	6.06	6.50	.79	5.7345	4.44	.86	5.4109	674.88	1.14	.000	2.0	1.8	.059
2230	7.11	6.11	.85	6.0065	4.50	.83	5.2426	674.88	.96	.000	2.0	1.8	.059
2300	5.72	8.44	.74	6.1362	5.61	.76	5.1875	674.88	1.11	.000	2.0	1.8	.059
2330	7.22	5.56	.83	5.6435	5.28	.84	5.6021	674.88	.93	.000	1.3	1.2	.059

AUGUST 29, 1967

HALF-HOURLY VALUES OF PARAMETERS IN THE HEAT BALANCE CALCULATIONS

TIME	MET SCRN TEMP (DEG C)	160 CM TEMP (DEG C)	160 CM R H	160 CM VAPRS (MM HG)	50 CM TEMP (DEG C)	50 CM R H	50 CM VAPRS (MM HG)	BAR PRS (MM HG)	RADN (MV)	PPTN (CM W)	90 CM WIND SPD (M/S)	60 CM WIND SPD (M/S)	ABLN (CM W)
0000	4.61	6.22	.79	5.6256	5.11	.80	5.2737	674.88	-1.39	.000	1.3	1.2	.084
0030	5.39	5.22	.83	5.5141	4.39	.84	5.2646	674.88	-1.07	.000	1.1	1.0	.084
0100	5.67	6.83	.84	6.2391	4.89	.98	6.3609	674.88	-1.04	.000	1.1	1.0	.084
0130	5.22	6.50	.78	5.6620	4.11	.92	5.6545	674.88	-1.18	.000	1.0	.9	.084
0200	4.56	5.17	.77	5.0957	4.72	.83	5.3248	674.88	-1.24	.000	1.0	.9	.084
0230	4.67	5.39	.80	5.3768	4.33	.83	5.1816	674.62	-1.11	.000	1.0	.9	.084
0300	5.56	6.67	.75	5.5071	6.22	.81	5.7680	674.62	.86	.000	1.0	.9	.084
0330	6.67	6.11	.90	6.3598	4.22	.94	5.8227	674.62	.43	.000	1.0	.9	.084
0400	6.00	5.72	.87	5.9844	5.22	.92	6.1120	674.62	-.70	.000	1.0	.9	.084
0430	7.22	7.22	.86	6.5606	5.83	.93	6.4466	674.62	.79	.000	1.7	1.6	.084
0500	6.94	8.06	.79	6.3798	5.28	.93	6.2024	674.62	-1.51	.000	1.7	1.6	.084
0530	6.94	9.17	.73	6.3566	6.11	.89	6.2892	674.62	-1.28	.000	1.6	1.5	.084
0600	7.22	10.28	.67	6.2865	7.50	.85	6.6089	674.62	-1.03	.000	1.6	1.5	.084
0630	8.89	10.83	.69	6.7188	8.06	.86	6.9451	674.37	1.69	.000	1.6	1.5	.084
0700	10.83	11.39	.75	7.5777	9.72	.76	6.8702	674.37	2.31	.000	1.6	1.5	.084
0730	10.28	9.72	.87	7.8645	8.33	.85	6.9953	674.37	3.87	.000	1.3	1.2	.084
0800	7.50	6.67	.89	6.5351	6.67	.82	6.0211	674.37	5.81	.000	1.3	1.2	.084
0830	8.89	9.39	.67	5.9222	5.67	.90	6.1669	674.37	7.06	.000	1.9	1.7	.084
0900	7.72	7.22	.65	4.9586	6.22	.71	5.0559	674.37	7.38	.000	1.9	1.7	.084
0930	7.22	6.67	.77	5.6540	5.56	.72	4.8956	674.37	10.30	.000	1.6	1.5	.084
1000	6.67	8.89	.69	5.8965	4.17	.87	5.3681	674.37	3.34	.000	1.6	1.5	.084
1030	11.56	11.67	.72	7.4097	10.61	.73	7.0037	674.62	5.50	.025	1.2	1.1	.084
1100	10.00	11.11	.71	7.0425	8.78	.75	6.3613	674.62	12.29	.038	1.2	1.1	.084
1130	9.50	9.72	.70	6.3278	10.94	.65	6.3763	674.62	4.52	.000	2.0	1.9	.084
1200	11.56	11.83	.69	7.1796	10.56	.70	6.6910	674.62	7.21	.000	2.0	1.9	.084
1230	10.39	9.28	.80	7.0186	8.44	.83	6.8825	674.62	15.40	.000	1.2	1.1	.084
1300	9.50	9.33	.75	6.6046	7.83	.79	6.2839	674.62	13.20	.000	1.2	1.1	.084
1330	7.61	9.00	.78	6.7159	7.78	.86	6.8148	674.62	9.56	.000	1.6	1.5	.084
1400	5.69	9.33	.77	6.7807	7.78	.83	6.5770	674.62	11.58	.000	1.6	1.5	.084
1430	8.22	7.61	.91	7.1293	5.28	.92	6.1357	674.37	12.12	.000	1.6	1.4	.084
1500	8.06	8.33	.73	6.0077	5.56	.99	6.7314	674.37	9.90	.000	1.6	1.4	.084
1530	7.83	6.67	.84	6.1679	5.78	.91	6.2837	674.37	5.38	.000	1.3	1.2	.084
1600	7.78	7.22	.85	6.4843	4.89	.95	6.1661	674.37	8.05	.025	1.3	1.2	.084
1630	6.67	7.22	.78	5.9503	6.11	.85	6.0065	673.86	8.08	.000	1.5	1.4	.084
1700	7.78	9.17	.76	6.6178	8.06	.86	6.9451	673.86	6.60	.000	1.5	1.4	.084
1730	9.17	11.94	.70	7.3373	10.28	.80	7.5062	673.86	4.65	.025	1.4	1.3	.084
1800	7.78	6.39	.88	6.3391	5.83	.89	6.1693	673.86	2.66	.000	1.4	1.3	.084
1830	7.22	8.89	.76	6.4947	6.39	.93	6.6992	673.35	3.17	.000	2.2	2.1	.084
1900	8.33	10.28	.71	6.6618	7.50	.85	6.6089	673.35	2.18	.000	2.2	2.1	.084
1930	10.28	8.89	.82	7.0075	7.22	.83	6.3317	673.35	1.60	.000	1.9	1.7	.084
2000	8.61	9.44	1.00	8.8723	10.00	.70	6.4469	673.35	1.11	.000	1.9	1.7	.084
2030	10.17	11.94	.73	7.6518	10.00	.77	7.0916	672.85	1.31	.000	1.9	1.8	.084
2100	10.06	11.83	.68	7.0756	10.06	.73	6.7483	672.85	.89	.000	1.9	1.8	.084
2130	12.11	13.89	.64	7.6198	10.61	.78	7.4834	672.85	1.49	.000	1.4	1.3	.084
2200	11.39	12.61	.68	7.4476	10.22	.71	6.6371	672.85	1.48	.000	1.4	1.3	.084
2230	11.11	10.11	.75	6.9590	8.61	.76	6.3737	672.59	1.38	.000	1.8	1.6	.084
2300	11.17	12.56	.69	7.5296	9.67	.79	7.1147	672.59	1.19	.038	1.8	1.6	.084
2330	11.39	12.39	.74	7.9872	11.11	.75	7.4392	672.59	1.18	.013	2.1	1.9	.084

APPENDIX F

FORTRAN IV PROGRAMS FOR HEAT BALANCE

LOGARITHMIC LAW

```
C  HEAT BALANCE PROGRAM
      DIMENSION TU(48),TL(48),TSCR(48),EU(48),EL(48),BPRS(48),MV(48),PPT
     1N(48),UU(48),UL(48),NZ(48),ZO(48), UZ(48), TAU(48),QR(48),QA(48),Q
     1L(48),QP(48),QM(48),H(48),RHU(48),RHL(48),TIME(48),DATE(10,12)
      REAL LATHT,MV,NTHETA,NU,NE,LGZ,LGAH ,NZ
      INTEGER TIME,DATE
      READ (5,1) NDAYS,CALIB,ZU,ZL,ZAU,ZAL
      DAZ=ZAU-ZAL
      DZ=ZU-ZL
      LGZ=ALOG10(ZU/ZL)
      LGAH=ALOG10(ZAU/ZAL)
      HTLN=ALOG(ZU/ZL)
      LATHT=600.
      CP=0.24
      TSEC=1800.
      CLPI=5.1959000
      AC=3.1473172
      B=.00295944
      CM=.0004191398
      CN=.0000001829924
      CS=.0000000008243516
      VK=0.4
      R=83.15
      ALZL=ALOG10(ZAL)
      ALZU=ALOG10(ZAU)
      RHOAIR=.00129
      CON=1./.4
      DO 400 L=1,NDAYS
      READ (5,2)(DATE(L,J),J=1,12)
      SUMQR=0.
      SUMQA=0.
      SUMQL=0.
      SUMQP=0.
      SUMQM=0.
      DO 300 I=1,48
      READ (5,3) TIME(I),TU(I),TL(I),TSCR(I),EU(I),EL(I),BPRS(I),MV(I),
     1PPTN(I),UU(I),UL(I),H(I),RHU(I),RHL(I)
C  CONVERSION OF TEMPERATURES FROM FAHRENHEIT TO CELSIUS
      TF=0.55555
      TU(I)=(TU(I)-32.)*TF
      TL(I)=(TL(I)-32.)*TF
      TSCR(I)=(TSCR(I)-32.)*TF
C  CALCULATION OF VAPOR PRESSURE
      T=273.+TU(I)
      X=(T-453.)/10.
      EUS=10.**(CLPI-(AC+X*(-B+X*(CM+X*(-CN+CS*X))))*(643.-T)/T)
      EU(I)=EUS*RHU(I)
      T=273.+TL(I)
      X=(T-453.)/10.
      ELS=10.**(CLPI-(AC+X*(-B+X*(CM+X*(-CN+CS*X))))*(643.-T)/T)
      EL(I)=ELS*RHL(I)
      H(I)=H(I)*0.9
      BPRS(I)=(BPRS(I)-2.60)*25.40
      PPTN(I)=(PPTN(I)*2.54)+0.0000001
C  CALCULATION OF THE COMPONENTS OF THE HEAT BALANCE EQUATION
      WS90=UU(I)*100.
      QR(I)=MV(I)*CALIB*30.
      ZO(I)=10.**((UU(I)*ALZL-UL(I)*ALZU)/(UU(I)-UL(I)))
      LD=0.
      SUMZO=0.
      DO 73 K=1,48
      IF(ZO(K).GT.1.) GO TO 73
      SUMZO=SUMZO+ZO(K)
      LD=LD+1
   73 CONTINUE
      AZO=SUMZO/FLOAT(LD)
      THT=ALOG(ZU/AZO)
      TAU(I)=RHOAIR*.16*ZAU*ZAU*((UU(I)-UL(I))*100./DAZ)**2
      UZ(I)=CON*SQRT((TAU*ABS(THT))/RHOAIR)
      TDEGK=((TU(I)+TL(I))/2.)+273.
      QA(I)=(RHOAIR*UZ(I)*CP*(TU(I)-TL(I))*VK*VK*1800.)/(THT*HTLN)
      QL(I)=(18.*VK*VK*(EU(I)-EL(I))*UZ(I))*1800./(R*THT*HTLN*TDEGK)
      QP(I)=TSCR(I)*PPTN(I)
      QM(I)=QR(I)+QA(I)+QL(I)+QP(I)
      SUMQR=SUMQR+QR(I)
      SUMQA=SUMQA+QA(I)
      SUMQL=SUMQL+QL(I)
      SUMQP=SUMQP+QP(I)
      SUMQM=SUMQM+QM(I)
      IF (I.EQ.48) PCQR=(SUMQR/SUMQM)*100.
      IF (I.EQ.48) PCQA=(SUMQA/SUMQM)*100.
      IF (I.EQ.48) PCQL=(SUMQL/SUMQM)*100.
      IF (I.EQ.48) PCQP=(SUMQP/SUMQM)*100.
  300 CONTINUE
      DO 200 I=1,48
      IF (I.EQ.1) WRITE (6,4)(DATE(L,J),J=1,4)
      WRITE (6,5) TIME(I),QR(I),QA(I),QL(I),QP(I),QM(I)
      IF (I.EQ.48) WRITE (6,10) SUMQR,SUMQA,SUMQL,SUMQP,SUMQM,PCQR,PCQA,
     1PCQL,PCQP
  200 CONTINUE
      DO 205 I=1,48
      IF (I.EQ.1) WRITE (6,9) (DATE(L,J),J=1,4)
      WRITE(6,11) TIME(I),TAU(I),ZO(I),UZ(I)
      IF(I.EQ.48) WRITE(6,12) AZO
  205 CONTINUE
  400 CONTINUE
  600 CONTINUE
    1 FORMAT(I4,5(3X,F6.3))
    2  FORMAT (12A6)
    3 FORMAT(A4,3F5.3,2F6.5,F7.4,F6.3,F4.2,2F3.2,F4.3,2F4.2)
    4 FORMAT(1H1,54X,4A6/1H0,23X,71HCONTRIBUTION OF EACH COMPONENT OF TH
     1E HEAT BALANCE EQUATION IN LANGLEYS/1H0,15X,4HTIME,16X,2HQR,14X,
     12HQA,15X,2HQL,16X,2HQP,14X,2HQM)
    5 FORMAT(1H ,15X,A4,F20.2,4(F17.2))
    9 FORMAT (1H1,54X,4A6/1H0,15X,4HTIME,11X,3HTAU,12X,2HZO,14X,2HUZ)
   10 FORMAT (1H0,19X,5HTOTAL,F15.2,4F17.2/1H0,19X,8HPER CENT,F11.0,2F16
     1.0,F17.0)
   11 FORMAT (1H ,15X,A4,3(F15.3))
   12 FORMAT (1H0,15X,13HAVERAGE ZO = ,F5.3)
      STOP
      END
```

```
C  HEAT BALANCE PROGRAM
       DIMENSION TU(48),TL(48),TSCR(48),EU(48),EL(48),BPRS(48),MV(48),PPT
      1N(48),UU(48),UL(48),NTHETA(48),NU(48),NE(48),A(48),QR(48),QA(48),Q
      1L(48),QP(48),QM(48),H(48),RHU(48),RHL(48),TIME(48),DATE(10,12)
       REAL LATHT,MV,NTHETA,NU,NE,LGZ,LGAH
       INTEGER TIME,DATE
       READ (5,1) NDAYS,CALIB,ZU,ZL,ZAU,ZAL
       DZ=ZU-ZL
       LGZ=ALOG10(ZU/ZL)
       LGAH=ALOG10(ZAU/ZAL)
       LATHT=600.
       CP=0.24
       TSEC=1800.
       CLPI=5.1959000
       AC=3.1473172
       B=.00295944
       CM=.0004191398
       CN=.0000001829924
       CS=.00000008243516
       DO 400 L=1,NDAYS
       READ (5,2)(DATE(L,J),J=1,12)
       SUMQR=0.
       SUMQA=0.
       SUMQL=0.
       SUMQP=0.
       SUMQM=0.
       DO 300 I=1,48
       READ (5,3) TIME(I),TU(I),TL(I),TSCR(I),EU(I),EL(I),BPRS(I),MV(I),
      1PPTN(I),UU(I),UL(I),H(I),RHU(I),RHL(I)
C  CONVERSION OF TEMPERATURES FROM FAHRENHEIT TO CELSIUS
       TF=0.55555
       TU(I)=(TU(I)-32.)*TF
       TL(I)=(TL(I)-32.)*TF
       TSCR(I)=(TSCR(I)-32.)*TF
C  CALCULATION OF VAPOR PRESSURE
       T=273.+TU(I)
       X=(T-453.)/10.
       EUS=10.**(CLPI-(AC+X*(-B+X*(CM+X*(-CN+CS*X))))*(643.-T)/T)
       EU(I)=EUS*RHU(I)
       T=273.+TL(I)
       X=(T-453.)/10.
       ELS=10.**(CLPI-(AC+X*(-B+X*(CM+X*(-CN+CS*X))))*(643.-T)/T)
       EL(I)=ELS*RHL(I)
C  CALCULATION OF POWER LAW INDICES
       NTHETA(I)=LGZ/ALOG10(TU(I)/TL(I))
       NU(I)=LGAH/ALOG10(UU(I)/UL(I))
       NE(I)=LGZ/ALOG10((ABS(EU(I)-4.58))/EL(I))
       H(I)=H(I)*0.9
       BPRS(I)=(BPRS(I)-2.60)*25.40
       PPTN(I)=(PPTN(I)*2.54)+0.0000001
C  CALCULATION OF THE COMPONENTS OF THE HEAT BALANCE EQUATION
       WS90=UU(I)*100.
       A(I)=(1.6E-4)*WS90*90.**(((NTHETA(I)-1.)/NTHETA(I))-1./NU(I))
       QR(I)=MV(I)*CALIB*30.
       QA(I)=A(I)*CP*((TU(I)-TL(I))/DZ)*1800.
       QL(I)=600.*A(I)*(0.623/BPRS(I))*((EU(I)-EL(I))/DZ)*1800.
       QP(I)=TSCR(I)*PPTN(I)
       QM(I)=QR(I)+QA(I)+QL(I)+QP(I)
       SUMQR=SUMQR+QR(I)
       SUMQA=SUMQA+QA(I)
       SUMQL=SUMQL+QL(I)
       SUMQP=SUMQP+QP(I)
       SUMQM=SUMQM+QM(I)
       IF (I.EQ.48) PCQR=(SUMQR/SUMQM)*100.
       IF (I.EQ.48) PCQA=(SUMQA/SUMQM)*100.
       IF (I.EQ.48) PCQL=(SUMQL/SUMQM)*100.
       IF (I.EQ.48) PCQP=(SUMQP/SUMQM)*100.
  300  CONTINUE
       DO 200 I=1,48
       IF (I.EQ.1) WRITE (6,4)(DATE(L,J),J=1,4)
       WRITE (6,5) TIME(I),QR(I),QA(I),QL(I),QP(I),QM(I)
       IF (I.EQ.48) WRITE (6,10) SUMQR,SUMQA,SUMQL,SUMQP,SUMQM,PCQR,PCQA,
      1PCQL,PCQP
  200  CONTINUE
       DO 201 I=1,48
       IF (I.EQ.1) WRITE (6,6)(DATE(L,J),J=1,4)
  201  WRITE (6,7) TIME(I),UL(I),UU(I),NU(I),TL(I),TU(I),NTHETA(I),EL(I),
      1EU(I),NE(I)
       DO 202 I=1,48
       IF (I.EQ.1) WRITE (6,8)(DATE(L,J),J=1,4)
  202  WRITE (6,9) TIME(I),TSCR(I),TU(I),RHU(I),EU(I),TL(I),RHL(I),EL(I),
      1BPRS(I),MV(I),PPTN(I),UU(I),UL(I),H(I)
  400  CONTINUE
  600  CONTINUE
    1  FORMAT(I4,5(3X,F6.3))
    2   FORMAT (12A6)
    3  FORMAT(A4,3F5.3,2F6.5,F7.4,F6.3,F4.2,2F3.2,F4.3,2F4.2)
    4  FORMAT(1H1,54X,4A6/1H0,23X,71HCONTRIBUTION OF EACH COMPONENT OF TH
      1E HEAT BALANCE EQUATION IN LANGLEYS/1H0,15X,4HTIME,16X,2HQR,14X,
      12HQA,15X,2HQL,16X,2HQP,14X,2HQM)
    5  FORMAT(1H ,15X,A4,F20.2,4(F17.2))
    6  FORMAT(1H1,54X,4A6/1H0,33X,52HWIND, TEMPERATURE AND VAPOR PRESSURE
      1 CHARACTERISTICS/1H0,20X,4HTIME,6X,6HWINDLR,3X,6HWINDUP,3X,2HNU,
      18X,3HT50,3X4HT160,3X,6HNTHETA,8X3HE50,5X,4HE160,5X,2HNE)
    7  FORMAT(1H ,20X,A4,F10.1,F9.1,F8.2,F11.2,F6.2,F9.2,F12.3,F8.3,F8.2,
      1F8.3)
    8  FORMAT(1H1,54X,4A6/1H0,27X,65HHALF-HOURLY VALUES OF PARAMETERS IN
      1THE HEAT BALANCE CALCULATIONS/1H0,9X,8HMET SCRN,9X,6H160 CM,16X,5H
      150 CM,38X,5H90 C.,6X,5H60 CM/1H ,2X,4HTIME,5X,4HTEMP,6X,2(4HTEMP,
      12X,3HR H,2X,5HVAPRS,5X),7HBAR PRS,4X,4HRADN,4X,4HPPTN,2(3X,8HWIND
      1SPD),3X,4HABLN/1H ,10X,7H(DEG C),2(3X,7H(DEG C),4X,7H(MM HG)),4X,
      17H(MM HG),4X,4H(MV),3X,6H(CM W),3X,5H(M/S),6X,5H(M/S),5X,6H(CM W))
    9  FORMAT(1H ,2X,A4,F9.2,F10.2,F5.2,F8.4,F8.2,F5.2,F8.4,F11.2,F9.2,F7
      1.3,F9.1,F11.1,F9.3)
   10  FORMAT (1H0,19X,5HTOTAL,F15.2,4F17.2/1H0,19X,8HPER CENT,F11.0,2F16

      1.0,F17.0)
       STOP
       END
```

APPENDIX G

COMPONENTS OF HEAT BALANCE EQUATION
USING THE LOGARITHMIC LAW

JULY 31, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QN
0000	-2.08	4.31	5.66	.00	7.89
0030	-1.67	.00	-3.67	.00	-5.35
0100	.49	4.54	4.67	.00	9.70
0130	.22	.00	7.96	.00	8.17
0200	.46	3.41	.86	.00	4.73
0230	.72	.32	3.51	.00	4.56
0300	.58	.80	2.33	.00	3.71
0330	.36	.32	5.55	.00	6.23
0400	.39	.00	-.40	.00	-.02
0430	.59	2.26	2.99	.00	5.85
0500	.79	2.96	4.15	.00	7.89
0530	1.10	.87	2.95	.00	4.92
0600	1.38	4.44	5.70	.00	11.52
0630	3.31	3.79	.35	.00	7.45
0700	3.09	1.09	1.91	.00	6.08
0730	3.53	3.99	2.24	.00	9.76
0800	2.13	.00	2.27	.00	4.40
0830	2.12	1.82	2.14	.00	6.08
0900	2.98	.00	2.28	.00	5.26
0930	4.10	-.91	-1.32	.00	1.87
1000	17.45	3.66	-1.06	.00	20.05
1030	8.24	.00	-2.38	.00	5.86
1100	11.09	4.62	2.18	.00	17.89
1130	10.88	4.66	3.87	.00	19.40
1200	7.68	2.80	8.48	.00	18.96
1230	7.03	1.68	2.00	.00	10.71
1300	9.62	1.13	-.40	.00	10.36
1330	8.58	2.10	1.45	.00	12.13
1400	6.44	2.29	4.28	.00	13.02
1430	7.14	6.32	9.94	.00	23.40
1500	5.96	5.59	3.19	.00	14.74
1530	8.77	2.71	3.42	.11	15.02
1600	7.83	1.36	2.59	.00	11.78
1630	5.22	3.89	3.04	.00	12.16
1700	5.66	3.14	3.68	.11	12.59
1730	4.07	.00	-1.06	.00	3.01
1800	2.14	1.59	1.07	.08	4.87
1830	2.46	.80	-.25	.04	3.04
1900	4.41	3.58	2.14	.05	10.18
1930	1.82	2.99	2.07	.00	6.88
2000	1.76	1.00	1.01	.25	4.02
2030	1.16	2.00	2.07	.00	5.23
2100	.76	1.01	1.12	.00	2.89
2130	.67	9.14	10.15	.00	19.96
2200	.60	.00	2.26	.30	3.19
2230	.56	7.16	10.05	.21	17.99
2300	.50	-4.11	5.23	.04	1.67
2330	.49	.00	2.44	.00	2.94
TOTAL	173.59	105.10	134.74	1.21	414.64
PER CENT	42.	25.	32.	0.	

AUG. 1, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	.51	.46	.60	.09	1.67
0030	.47	.46	-.24	.18	.87
0100	.51	1.03	.49	.11	2.15
0130	.49	.41	.54	.10	1.55
0200	.42	.36	1.04	.09	1.91
0230	.49	1.30	1.10	.15	3.04
0300	.38	-.10	.78	.20	1.25
0330	.46	1.04	.23	.21	1.94
0400	.49	.00	.14	.10	.73
0430	.48	-.62	-.63	.04	-.73
0500	.60	.21	.59	.00	1.40
0530	1.21	-.26	-.11	.03	.87
0600	1.48	.05	.30	.00	1.82
0630	1.48	1.64	1.87	.07	5.06
0700	2.22	.51	1.12	.00	3.85
0730	2.97	.87	1.10	.03	4.97
0800	4.28	1.03	-.17	.08	5.21
0830	4.49	2.05	2.60	.09	9.24
0900	5.64	1.29	.71	.11	7.94
0930	6.57	.26	1.40	.03	8.26
1000	5.46	2.59	2.17	.04	10.27
1030	6.28	1.56	.97	.04	8.85
1100	8.44	1.30	1.33	.00	11.08
1130	7.66	.52	.56	.13	8.86
1200	7.95	1.15	1.79	.16	11.05
1230	10.55	2.26	2.13	.16	15.09
1300	8.41	.21	2.23	.22	11.08
1330	6.05	.37	.69	.06	7.16
1400	4.92	1.10	1.77	.06	7.85
1430	7.22	1.63	3.29	.24	12.38
1500	6.31	1.63	1.90	.07	9.91
1530	3.52	.84	.45	.28	5.10
1600	3.98	-.63	-.55	.04	2.84
1630	4.79	.89	1.27	.03	6.98
1700	4.65	-1.52	-.89	.12	2.36
1730	4.04	.79	1.45	.25	6.53
1800	1.95	3.67	3.36	.14	9.11
1830	1.81	1.26	1.45	.12	4.64
1900	3.02	1.21	1.40	.00	5.63
1930	1.96	2.37	1.53	.10	5.96
2000	1.46	.79	1.66	.24	4.14
2030	1.26	1.85	2.69	.21	6.01
2100	1.00	.80	.39	.30	2.48
2130	.66	-.53	-.60	.24	-.23
2200	.60	.80	.90	.27	2.57
2230	.59	1.32	2.09	.16	4.17
2300	.64	2.12	2.45	.38	5.59
2330	.56	-.53	.58	.22	.84
TOTAL	151.62	41.80	51.91	6.00	251.33
PER CENT	60.	17.	21.	2.	

AUG. 2, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	.65	.74	1.39	.46	3.24
0030	.60	.90	1.04	.25	2.79
0100	.48	.90	1.53	.13	3.03
0130	.50	.32	1.09	.22	2.14
0200	.56	1.31	2.34	.26	4.47
0230	.58	1.46	1.58	.00	3.63
0300	.59	.21	.92	.10	1.82
0330	.49	.05	.05	.08	.67
0400	.48	1.00	1.14	.07	2.68
0430	.67	1.36	1.05	.11	3.18
0500	.68	.89	1.38	.25	3.20
0530	.73	1.52	1.73	.13	4.12
0600	.87	2.04	.89	.31	4.11
0630	1.60	-1.62	-1.73	.19	-1.55
0700	1.93	-.21	.62	.13	2.47
0730	3.78	1.89	1.63	.10	7.40
0800	4.50	-1.05	-1.11	.05	2.39
0830	5.81	1.05	2.61	.00	9.47
0900	7.91	1.57	4.46	.00	13.95
0930	6.82	1.05	1.85	.00	9.72
1000	7.73	1.04	2.27	.00	11.04
1030	7.12	1.82	1.93	.00	10.87
1100	11.84	1.04	1.26	.00	14.14
1130	8.98	.52	.50	.00	9.99
1200	6.87	-.67	2.01	.00	8.21
1230	11.63	1.44	1.76	.00	14.83
1300	11.23	.05	-.53	.00	10.75
1330	15.55	1.03	1.75	.00	18.32
1400	15.09	.10	-.03	.00	15.16
1430	13.78	.26	-.14	.00	13.90
1500	14.20	.26	2.58	.00	17.03
1530	8.32	1.13	1.31	.00	10.76
1600	10.71	.36	.78	.00	11.85
1630	11.99	.92	.74	.00	13.65
1700	14.51	.97	.63	.00	16.11
1730	13.59	1.63	2.44	.00	17.66
1800	6.45	1.17	1.28	.00	8.91
1830	3.56	.46	.60	.07	4.70
1900	3.53	.41	.14	.00	4.09
1930	2.35	.78	.35	.00	3.48
2000	2.23	.26	.25	.00	2.73
2030	1.44	1.30	1.36	.00	4.09
2100	1.12	1.29	.72	.00	3.13
2130	.81	.26	.77	.00	1.84
2200	.71	.26	.24	.00	1.21
2230	.65	.77	.48	.00	1.91
2300	-.07	.00	.00	.00	-.07
2330	-.28	.52	-.78	.00	-.55

TOTAL	245.92	34.71	49.11	2.92	332.65
PER CENT	74.	10.	15.	1.	

AUG. 3, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QW
0000	-.58	8.54	7.24	.00	15.19
0030	-1.02	3.42	4.02	.00	6.42
0100	.54	5.59	3.78	.00	9.92
0130	.62	2.03	1.86	.00	4.52
0200	-.59	6.28	5.59	.00	11.28
0230	-.66	3.78	8.63	.00	11.75
0300	-.74	6.18	6.06	.00	11.49
0330	-1.21	5.68	5.93	.00	10.40
0400	-.99	1.57	-.14	.00	.44
0430	-.81	7.26	2.59	.00	9.04
0500	-.68	7.15	5.19	.00	11.66
0530	-.24	8.43	9.94	.00	18.12
0600	.02	3.97	1.48	.00	5.47
0630	1.80	3.18	1.51	.00	6.49
0700	5.31	2.38	.01	.00	7.70
0730	7.79	7.95	.57	.00	16.31
0800	10.52	8.74	6.01	.00	25.28
0830	12.40	3.94	3.90	.00	20.24
0900	14.45	7.80	3.20	.00	25.46
0930	15.79	4.68	.95	.00	21.42
1000	17.69	5.46	3.63	.00	26.79
1030	20.36	6.24	-1.00	.00	25.60
1100	21.38	9.36	2.72	.00	33.46
1130	21.93	4.68	2.70	.00	29.31
1200	21.78	4.37	-.93	.00	25.22
1230	17.55	5.93	2.86	.00	26.34
1300	24.29	7.02	.33	.00	31.65
1330	23.95	3.91	1.52	.00	29.37
1400	22.01	5.32	-.58	.00	26.75
1430	21.30	2.04	2.74	.00	26.09
1500	20.16	7.86	1.42	.00	29.44
1530	18.96	.16	2.82	.00	21.94
1600	17.60	3.73	.19	.00	21.52
1630	15.85	4.97	.51	.00	21.33
1700	13.88	1.55	2.65	.00	18.08
1730	11.86	1.55	1.38	.00	14.79
1800	9.05	3.11	1.02	.00	13.18
1830	7.30	9.25	4.24	.00	20.79
1900	5.03	3.83	4.03	.00	12.88
1930	3.03	2.30	2.59	.00	7.92
2000	.72	3.83	4.03	.00	8.58
2030	-1.45	3.06	.72	.00	2.34
2100	-1.79	1.53	1.01	.00	.74
2130	-2.11	3.84	-.17	.00	1.56
2200	-2.19	8.49	4.26	.00	10.56
2230	-2.27	4.63	2.50	.00	4.86
2300	-2.23	.77	2.69	.00	1.23
2330	-2.26	5.40	5.47	.00	8.62
TOTAL	383.13	232.75	133.66	.00	749.54
PER CENT	51.	31.	18.	0.	

AUGUST 26, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QW
0000	.57	2.33	-5.62	.00	-2.71
0030	.70	.47	-.80	.33	.70
0100	.54	-.12	1.51	.22	2.16
0130	.27	1.18	.52	.00	1.97
0200	.33	1.13	-.36	.00	1.10
0230	.60	1.84	.64	.00	3.08
0300	.49	.26	1.03	.41	2.20
0330	.57	1.14	.94	.49	3.15
0400	.49	1.75	1.77	.74	4.75
0430	.41	-.88	-.68	.18	-.97
0500	.48	-.44	.53	.40	.96
0530	.49	.09	1.02	.28	1.87
0600	.55	.88	-1.03	.30	.70
0630	.61	.44	1.38	.25	2.69
0700	.73	.44	.44	.42	2.04
0730	1.65	-1.33	2.81	.30	3.43
0800	1.39	1.16	.23	.27	3.05
0830	1.61	.45	.68	.19	2.94
0900	2.27	1.62	1.19	.14	5.23
0930	2.59	2.26	2.25	.30	7.41
1000	3.03	2.26	3.03	.05	8.37
1030	2.64	-.19	2.46	.00	4.92
1100	3.53	1.89	2.67	.05	8.14
1130	3.34	1.23	1.24	.05	5.86
1200	3.53	1.04	-2.40	.30	2.47
1230	4.46	2.95	2.35	.26	10.02
1300	4.83	2.10	.32	.32	7.57
1330	4.10	3.15	2.18	.05	9.48
1400	5.75	.10	.62	.17	6.63
1430	4.68	2.10	.30	.00	7.08
1500	4.08	1.14	-.93	.33	4.62
1530	2.45	2.49	1.19	.04	6.16
1600	2.47	1.25	.25	.23	4.20
1630	2.43	1.92	.90	.05	5.29
1700	2.15	.96	-.08	.15	3.17
1730	1.52	1.92	.90	.26	4.61
1800	1.53	.96	1.03	.11	3.64
1830	1.03	1.45	1.52	.32	4.31
1900	1.01	1.45	1.51	.32	4.29
1930	.74	1.93	2.22	.05	4.95
2000	.64	.97	1.02	.05	2.68
2030	.60	2.33	2.16	.30	5.40
2100	.58	1.46	.46	.36	2.86
2130	.56	1.66	.40	.20	2.82
2200	.50	2.63	2.76	.25	6.14
2230	.57	1.56	1.88	.14	4.15
2300	.48	1.96	2.03	.15	4.61
2330	.50	.79	.56	.11	1.96
TOTAL	81.13	60.14	40.98	9.69	192.13
PER CENT	42.	31.	21.	5.	

AUGUST 27, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	.49	1.18	1.29	.06	3.02
0030	.55	.92	.56	.29	2.32
0100	.46	1.01	.89	.00	2.38
0130	.48	.32	-.01	.19	.98
0200	.49	.35	.36	.17	1.38
0230	.53	.58	1.30	.00	2.42
0300	.54	.49	.15	.00	1.18
0330	.48	.13	.22	.05	.87
0400	.45	1.10	.52	.05	2.11
0430	.34	.97	-.13	.00	1.18
0500	.45	.49	.56	.00	1.49
0530	.41	.49	.22	.00	1.11
0600	.52	.16	.15	.00	.84
0630	1.07	.33	-.03	.00	1.37
0700	1.46	.32	-.03	.00	1.75
0730	1.95	.03	.03	.03	2.04
0800	3.88	.03	.36	.00	4.28
0830	5.94	.33	.21	.00	6.48
900	6.64	.33	.12	.00	7.09
930	16.43	.49	.65	.00	17.57
1000	10.87	.88	.75	.00	12.50
1030	13.53	.38	.68	.00	14.59
1100	18.04	1.19	.87	.00	20.10
1130	17.54	1.77	.84	.00	20.15
1200	15.85	1.31	.43	.00	17.59
1230	15.48	.88	.89	.00	17.25
1300	12.43	.29	.35	.00	13.08
1330	17.03	.16	.52	.00	17.71
1400	12.88	1.01	.34	.00	14.23
1430	13.42	.46	-.02	.00	13.86
1500	13.59	.20	.78	.00	14.57
1530	19.60	.76	-.12	.00	20.25
1600	10.79	.17	.71	.00	11.67
1630	8.10	.17	.15	.00	8.42
1700	5.15	.67	.26	.00	6.07
1730	4.63	1.17	.06	.00	5.86
1800	3.79	.67	-.13	.00	4.33
1830	1.55	.03	.75	.00	2.34
1900	.62	.84	.03	.00	1.49
1930	-.63	-.17	-.14	.00	-.94
2000	-1.79	1.51	1.55	.00	1.27
2030	-2.49	1.34	-.12	.00	-1.27
2100	-2.84	1.51	.00	.00	-1.33
2130	-2.98	.13	.40	.00	-2.45
2200	-3.00	1.27	.11	.00	-1.62
2230	-2.87	.60	.64	.00	-1.63
2300	-2.84	1.24	1.38	.00	-.22
2330	-2.77	.37	.08	.00	-2.32
TOTAL	236.27	30.87	19.42	.84	287.40
PER CENT	82.	11.	7.	0.	

AUGUST 28, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	-2.47	.37	.20	.00	-1.91
0030	-2.47	.61	.19	.00	-1.68
0100	-2.69	1.33	2.19	.00	.82
0130	-2.69	.48	.57	.00	-1.65
0200	-2.58	.75	-.09	.00	-1.92
0230	-2.37	1.92	.90	.00	.45
0300	-1.63	.68	-.38	.00	-1.52
0330	-1.56	2.50	.89	.00	1.82
0400	-1.04	1.65	1.87	.00	2.47
0430	-.91	1.72	-.21	.00	.60
0500	-.86	.17	-.29	.00	-.98
0530	-1.00	.86	.41	.00	.27
0600	-.39	.34	.43	.00	.39
0630	.02	1.56	-.12	.00	1.46
0700	1.28	.70	.50	.00	2.47
0730	2.66	1.22	.17	.00	4.05
0800	3.58	.52	-.36	.00	3.75
0830	3.87	2.06	1.43	.00	7.37
0900	4.84	2.28	.91	.00	8.03
0930	4.36	1.09	1.15	.00	6.60
1000	7.46	.99	.27	.00	8.72
1030	10.61	1.59	1.31	.00	13.51
1100	9.43	2.33	.25	.00	12.01
1130	11.12	.81	-.18	.00	11.75
1200	11.47	.52	-.09	.00	11.91
1230	15.09	.73	-.07	.00	15.75
1300	13.76	.21	.81	.00	14.78
1330	22.01	1.36	1.82	.00	25.20
1400	12.12	1.22	-.22	.00	13.12
1430	12.85	.63	-.68	.00	12.80
1500	12.10	.91	.02	.00	13.03
1530	10.64	.73	-.38	.00	10.99
1600	8.12	.42	.09	.00	8.62
1630	9.65	.35	.10	.00	10.10
1700	6.10	1.05	.46	.00	7.61
1730	5.16	1.40	-.00	.00	6.55
1800	4.11	1.39	1.02	.00	6.52
1830	2.91	1.04	.38	.00	4.33
1900	1.90	1.91	-.27	.00	3.54
1930	1.41	.52	.57	.00	2.50
2000	.69	1.21	-1.00	.00	.90
2030	.31	.59	.41	.00	1.31
2100	.56	2.32	.81	.00	3.69
2130	.87	.76	.54	.00	2.18
2200	1.13	1.29	.51	.00	2.93
2230	.95	1.02	1.21	.00	3.18
2300	1.10	1.79	1.50	.00	4.39
2330	.92	.18	.07	.00	1.16

TOTAL	192.29	52.09	19.59	.00	263.97
PER CENT	73.	20.	7.	0.	

AUGUST 29, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	-1.38	.70	.56	.00	-.12
0030	-1.06	.53	.40	.00	-.14
0100	-1.03	1.22	-.19	.00	.00
0130	-1.17	1.51	.01	.00	.35
0200	-1.23	.28	-.36	.00	-1.31
0230	-1.10	.67	.31	.00	-.12
0300	.85	.28	-.41	.00	.72
0330	.43	1.20	.86	.00	2.48
0400	-.69	.32	-.20	.00	-.56
0430	.78	.88	.18	.00	1.84
0500	-1.49	1.76	.28	.00	.54
0530	-1.27	1.93	.11	.00	.77
0600	-1.02	1.76	-.51	.00	.23
0630	1.67	1.75	-.35	.00	3.07
0700	2.29	1.04	1.09	.00	4.42
0730	3.83	.87	1.35	.00	6.05
0800	5.75	.00	.80	.00	6.56
0830	6.99	2.33	-.38	.00	8.94
0900	7.31	.63	-.15	.00	7.78
0930	10.20	.69	1.19	.00	12.08
1000	3.31	2.93	.82	.00	7.06
1030	5.44	.66	.62	.29	7.01
1100	12.17	1.45	1.05	.38	15.04
1130	4.47	-.76	-.07	.00	3.64
1200	7.14	.79	.75	.00	8.68
1230	15.25	.52	.21	.00	15.97
1300	13.07	.93	.49	.00	14.49
1330	9.46	.76	-.15	.00	10.07
1400	11.46	.97	.31	.00	12.74
1430	12.00	1.45	1.54	.00	14.99
1500	9.80	1.72	-1.12	.00	10.40
1530	5.33	.55	-.18	.00	5.70
1600	7.97	1.45	.49	.20	10.11
1630	8.00	.69	-.09	.00	8.60
1700	6.53	.69	-.50	.00	6.72
1730	4.60	1.03	-.26	.23	5.61
1800	2.63	.34	.26	.00	3.24
1830	3.14	1.55	-.32	.00	4.37
1900	2.16	1.72	.08	.00	3.96
1930	1.58	1.04	1.04	.00	3.66
2000	1.10	-.35	3.75	.00	4.50
2030	1.30	1.21	.86	.00	3.37
2100	.88	1.11	.50	.00	2.49
2130	1.48	2.04	.21	.00	3.72
2200	1.47	1.48	1.24	.00	4.18
2230	1.37	.93	.90	.00	3.19
2300	1.18	1.78	.63	.43	4.01
2330	1.17	.79	.83	.14	2.93
TOTAL	184.11	49.80	18.47	1.68	254.05
PER CENT	72.	20.	7.	1.	

APPENDIX H

COMPONENTS OF HEAT BALANCE EQUATION USING THE POWER LAW

JULY 31, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QV
0000	-2.08	1.45	1.74	.00	1.11
0030	-1.67	.00	-.00	.00	-1.67
0100	.49	4.83	4.52	.00	9.84
0130	.22	.00	.00	.00	.22
0200	.46	1.12	.26	.00	1.83
0230	.72	.47	4.64	.00	5.83
0300	.58	.41	1.06	.00	2.07
0330	.36	.23	3.55	.00	4.14
0400	.39	.00	-.00	.00	.39
0430	.59	.00	.00	.00	.59
0500	.79	.67	.85	.00	2.30
0530	1.10	.60	1.84	.00	3.54
0600	1.38	.00	.00	.00	1.38
0630	3.31	.00	.00	.00	3.31
0700	3.09	.44	.70	.00	4.23
0730	3.53	.44	.22	.00	4.20
0800	2.13	.00	.00	.00	2.13
0830	2.12	.62	.66	.00	3.40
0900	2.98	.00	.00	.00	2.98
0930	4.10	-1.95	-2.56	.00	-.42
1000	17.45	6.13	-1.61	.00	21.97
1030	8.24	.00	-.00	.00	8.24
1100	11.09	1.28	.55	.00	12.91
1130	10.88	.98	.74	.00	12.61
1200	7.68	.19	.52	.00	8.40
1230	7.03	.15	.16	.00	7.34
1300	9.62	.00	-.00	.00	9.62
1330	8.58	.00	.00	.00	8.58
1400	6.44	.87	1.48	.00	8.79
1430	7.14	.90	1.29	.00	9.32
1500	5.96	.92	.48	.00	7.36
1530	8.77	1.53	1.77	.11	12.18
1600	7.83	.36	.62	.00	8.81
1630	5.22	.50	.36	.00	6.08
1700	5.66	.00	.00	.11	5.78
1730	4.07	.00	-.00	.00	4.07
1800	2.14	.99	.60	.08	3.82
1830	2.46	.69	-.20	.04	2.99
1900	4.41	2.77	1.51	.05	8.74
1930	1.82	2.61	1.65	.00	6.08
2000	1.76	.72	.66	.25	3.39
2030	1.16	1.12	1.06	.00	3.34
2100	.76	.00	.00	.00	.76
2130	.67	.00	.00	.00	.67
2200	.60	.00	.00	.30	.90
2230	.56	1.29	1.65	.21	3.71
2300	.50	-4.93	5.71	.04	1.33
2330	.49	.00	.00	.00	.50
TOTAL	173.59	28.38	36.51	1.21	239.68
PER CENT	72.	12.	15.	1.	

AUG. 1, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	.51	5.73	6.79	.09	13.12
0030	.47	5.62	-2.69	.16	3.58
0100	.51	.76	.33	.11	1.71
0130	.49	.39	.46	.10	1.44
0200	.42	.47	1.24	.09	2.22
0230	.49	.79	.62	.15	2.06
0300	.38	-.15	1.05	.20	1.47
0330	.46	.54	.11	.21	1.32
0400	.49	.00	.00	.10	.59
0430	.48	-4.02	-3.73	.04	-7.24
0500	.60	1.54	4.03	.00	6.18
0530	1.21	-4.17	-1.64	.03	-4.57
0600	1.48	.00	.00	.00	1.48
0630	1.48	.00	.00	.07	1.55
0700	2.22	.82	1.63	.00	4.67
0730	2.97	.88	1.01	.03	4.90
0800	4.28	.22	-.03	.06	4.55
0830	4.49	.23	.26	.09	5.07
0900	5.84	.00	.00	.11	5.95
0930	6.57	.00	.00	.03	6.61
1000	5.46	.00	.00	.04	5.50
1030	6.28	.00	.00	.04	6.32
1100	8.44	.00	.00	.00	8.44
1130	7.66	.00	.00	.13	7.80
1200	7.95	.00	.00	.16	8.11
1230	10.55	.00	.00	.16	10.71
1300	8.41	.17	1.63	.22	10.44
1330	6.05	.25	.42	.06	6.78
1400	4.92	1.58	2.33	.06	8.89
1430	7.22	2.25	4.19	.24	13.90
1500	6.31	12.87	13.79	.07	33.04
1530	3.52	11.96	5.90	.28	21.67
1600	3.98	-1.74	-1.39	.04	.59
1630	4.79	.66	.86	.03	6.34
1700	4.65	-27.28	-14.63	.12	-37.14
1730	4.04	1.61	2.71	.25	8.62
1800	1.95	.34	.29	.14	2.71
1830	1.81	1.38	1.46	.12	4.77
1900	3.02	.56	.59	.00	4.16
1930	1.96	.57	.34	.10	2.97
2000	1.46	2.80	5.36	.24	9.86
2030	1.26	2.55	3.39	.21	7.41
2100	1.00	2.29	1.02	.30	4.61
2130	.66	-4.45	-4.61	.24	-8.16
2200	.60	3.22	3.34	.27	7.43
2230	.59	3.73	5.40	.16	9.88
2300	.64	.75	.79	.36	2.56
2330	.56	-1.35	1.35	.22	.79
TOTAL	151.62	24.38	43.97	6.00	225.96
PER CENT	67.	11.	19.	3.	

AUG. 2, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	.65	3.27	5.59	.46	9.98
0030	.60	2.14	2.25	.25	5.24
0100	.48	2.38	3.72	.13	6.70
0130	.50	2.52	7.96	.22	11.21
0200	.56	4.37	7.13	.26	12.32
0230	.58	2.10	2.06	.00	4.77
0300	.59	.87	3.46	.10	5.02
0330	.49	.30	.26	.08	1.13
0400	.48	1.45	1.50	.07	3.50
0430	.67	1.04	.72	.11	2.54
0500	.68	1.91	2.71	.25	5.55
0530	.73	.01	.01	.13	.88
0600	.87	.00	.00	.31	1.19
0630	1.60	-2.25	-2.16	.19	-2.63
0700	1.93	-.07	.19	.13	2.18
0730	3.78	.28	.22	.10	4.37
0800	4.50	-5.57	-5.36	.05	-6.38
0830	5.81	.58	1.32	.00	7.71
0900	7.91	.53	1.38	.00	9.81
0930	6.82	1.11	1.81	.00	9.74
1000	7.73	.82	1.63	.00	10.19
1030	7.12	.06	.06	.00	7.24
1100	11.84	.09	.10	.00	12.03
1130	8.98	.44	.38	.00	9.80
1200	6.87	-1.79	4.92	.00	10.00
1230	11.63	.13	.15	.00	11.92
1300	11.23	.01	-.14	.00	11.10
1330	15.55	.80	1.25	.00	17.61
1400	15.09	.18	-.06	.00	15.21
1430	13.78	.12	-.06	.00	13.84
1500	14.20	.13	1.22	.00	15.54
1530	8.32	.06	.06	.00	8.43
1600	10.71	.05	.09	.00	10.85
1630	11.99	2.51	1.83	.00	16.32
1700	14.51	2.76	1.63	.00	18.90
1730	13.59	.03	.04	.00	13.67
1800	6.45	.03	.03	.00	6.51
1830	3.56	1.53	1.80	.07	6.97
1900	3.53	1.40	.44	.00	5.38
1930	2.35	2.04	.84	.00	5.23
2000	2.23	1.15	.99	.00	4.38
2030	1.44	.61	.58	.00	2.62
2100	1.12	.70	.36	.00	2.17
2130	.81	1.50	4.11	.00	6.43
2200	.71	1.55	1.34	.00	3.61
2230	.65	.08	.04	.00	.78
2300	-.07	.00	.00	.00	-.07
2330	-.28	.42	-.58	.00	-.44
TOTAL	245.92	34.38	57.83	2.92	341.05
PER CENT	72.	10.	17.	1.	

AUG. 3, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	-.58	.10	.06	.00	-.41
0030	-1.02	1.19	1.28	.00	1.45
0100	.54	.46	.28	.00	1.29
0130	.62	.76	.63	.00	2.01
0200	-.59	.43	.35	.00	.16
0230	-.66	.58	1.20	.00	1.11
0300	-.74	.17	.15	.00	-.43
0330	-1.21	.19	.18	.00	-.84
0400	-.99	.15	-.01	.00	-.65
0430	-.81	.11	.04	.00	-.67
0500	-.68	.06	.04	.00	-.58
0530	-.24	.62	.67	.00	1.06
0600	.02	1.25	.42	.00	1.70
0630	1.80	1.18	.51	.00	3.49
0700	5.31	1.55	.01	.00	6.86
0730	7.79	.68	.04	.00	8.51
0800	10.52	.92	.58	.00	12.02
0830	12.40	2.91	2.63	.00	17.94
0900	14.45	2.03	.76	.00	17.25
0930	15.79	.75	.14	.00	16.68
1000	17.69	.89	.54	.00	19.12
1030	20.36	1.21	-.18	.00	21.39
1100	21.38	.79	.21	.00	22.39
1130	21.93	1.19	.63	.00	23.75
1200	21.78	1.31	-.26	.00	22.84
1230	17.55	1.77	.78	.00	20.10
1300	24.29	1.59	.07	.00	25.95
1330	23.95	3.22	1.14	.00	28.32
1400	22.01	2.47	-.24	.00	24.24
1430	21.30	2.66	3.27	.00	27.23
1500	20.16	2.08	.34	.00	22.58
1530	18.96	.50	8.31	.00	27.78
1600	17.60	4.06	.19	.00	21.65
1630	15.85	4.10	.39	.00	20.34
1700	13.88	3.46	5.37	.00	22.71
1730	11.86	1.12	.90	.00	13.68
1800	9.05	1.46	.44	.00	10.95
1830	7.30	1.67	.70	.00	9.67
1900	5.03	3.12	3.00	.00	11.14
1930	3.03	2.39	2.47	.00	7.89
2000	.72	2.48	2.36	.00	5.58
2030	-1.45	1.22	.26	.00	.04
2100	-1.79	.95	.57	.00	-.27
2130	-2.11	1.82	-.07	.00	-.36
2200	-2.19	1.09	.50	.00	-.60
2230	-2.27	.84	.41	.00	-1.02
2300	-2.23	.60	1.89	.00	.26
2330	-2.26	.87	.80	.00	-.59
TOTAL	383.13	66.99	44.78	.00	494.90
PER CENT	77.	14.	9.	0.	

AUGUST 26, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	GM
0000	.57	1.04	-2.31	.00	-.70
0030	.70	.41	-.65	.33	.79
0100	.54	-.13	1.55	.22	2.19
0130	.27	1.00	.41	.00	1.67
0200	.33	.86	-.25	.00	.93
0230	.60	.42	.14	.00	1.16
0300	.49	.18	.65	.41	1.73
0330	.57	.17	.13	.49	1.37
0400	.49	.22	.21	.74	1.65
0430	.41	-3.53	-2.53	.18	-5.47
0500	.48	-1.47	1.63	.40	1.03
0530	.49	.05	.57	.28	1.36
0600	.55	.34	-.37	.30	.82
0630	.61	.16	.47	.25	1.50
0700	.73	.16	.15	.42	1.47
0730	1.65	-7.71	15.01	.30	9.26
0800	1.39	1.32	.25	.27	3.22
0830	1.61	.61	.86	.19	3.27
0900	2.27	1.10	.75	.14	4.26
0930	2.59	.67	.61	.30	4.17
1000	3.03	.69	.85	.05	4.62
1030	2.64	-.22	2.72	.00	5.14
1100	3.53	.78	1.02	.05	5.38
1130	3.34	.24	.22	.05	3.85
1200	3.53	.20	-.43	.30	3.60
1230	4.46	.76	.56	.26	6.04
1300	4.83	.93	.13	.32	6.21
1330	4.10	3.25	2.07	.05	9.47
1400	5.75	.43	2.59	.17	8.94
1430	4.68	3.14	.41	.00	8.23
1500	4.08	2.45	-1.84	.33	5.02
1530	2.45	.85	.38	.04	3.71
1600	2.47	.89	.17	.23	3.77
1630	2.43	3.17	1.37	.05	7.02
1700	2.15	2.38	-.19	.15	4.48
1730	1.52	1.38	.60	.26	3.77
1800	1.53	1.10	1.09	.11	3.63
1830	1.03	.76	.73	.32	2.84
1900	1.01	.85	.81	.32	2.99
1930	.74	2.24	2.36	.05	5.39
2000	.64	1.98	1.92	.05	4.65
2030	.60	.82	.70	.30	2.42
2100	.58	.83	.24	.36	2.01
2130	.56	1.78	.39	.20	2.93
2200	.50	1.49	1.43	.25	3.67
2230	.57	1.22	1.35	.14	3.28
2300	.48	1.31	1.24	.15	3.18
2330	.50	1.24	.82	.11	2.67
TOTAL	81.13	32.83	40.96	9.89	164.81
PER CENT	49.	20.	25.	6.	

AUGUST 27, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	CM
0000	.49	1.28	1.28	.06	3.11
0030	.55	.85	.48	.29	2.17
0100	.48	.55	.45	.00	1.47
0130	.48	1.12	-.04	.19	1.74
0200	.49	1.22	1.14	.17	3.02
0230	.53	1.24	2.55	.00	4.32
0300	.54	1.23	.35	.00	2.13
0330	.48	.56	.87	.05	1.95
0400	.45	1.27	.54	.05	2.31
0430	.34	.61	-.08	.00	.87
0500	.45	.64	.67	.00	1.75
0530	.41	.94	.38	.00	1.72
0600	.52	.50	.43	.00	1.45
0630	1.07	.98	-.07	.00	1.98
0700	1.46	.98	-.07	.00	2.37
0730	1.95	.17	.15	.03	2.30
0800	3.88	.18	1.80	.00	5.86
0830	5.94	.19	.11	.00	6.24
900	6.64	.20	.07	.00	6.91
930	16.43	.77	.95	.00	18.16
1000	10.87	.72	.56	.00	12.15
1030	13.53	1.44	2.32	.00	17.30
1100	18.04	1.47	.99	.00	20.49
1130	17.54	.61	.27	.00	18.42
1200	15.85	.72	.22	.00	16.78
1230	15.48	1.03	.95	.00	17.47
1300	12.43	.65	.70	.00	13.79
1330	17.03	.99	2.86	.00	20.88
1400	12.88	1.55	.47	.00	14.90
1430	13.42	1.17	-.05	.00	14.55
1500	13.59	.80	2.88	.00	17.26
1530	19.60	1.61	-.23	.00	20.99
1600	10.79	.74	2.89	.00	14.42
1630	8.10	1.13	.93	.00	10.16
1700	5.15	1.30	.45	.00	6.90
1730	4.63	1.16	.05	.00	5.85
1800	3.79	.83	-.15	.00	4.47
1830	1.55	.16	3.24	.00	4.96
1900	.62	1.45	.05	.00	2.12
1930	-.63	-.81	-.63	.00	-2.08
2000	-1.79	.94	.88	.00	.03
2030	-2.49	4.47	-.36	.00	1.63
2100	-2.84	2.11	.00	.00	-.73
2130	-2.98	.80	2.16	.00	.03
2200	-3.00	1.10	.08	.00	-1.81
2230	-2.87	1.18	1.15	.00	-.55
2300	-2.84	.84	.85	.00	-1.15
2330	-2.77	.43	.08	.00	-2.26
TOTAL	236.27	46.06	35.59	.84	318.76
PER CENT	74.	14.	11.	0.	

AUGUST 28, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	-2.47	.39	.19	.00	-1.69
0030	-2.47	.74	.21	.00	-1.53
0100	-2.69	.87	1.32	.00	-.51
0130	-2.69	.95	1.04	.00	-.70
0200	-2.58	1.45	-.15	.00	-1.29
0230	-2.37	.34	.15	.00	-1.88
0300	-1.83	.62	-.32	.00	-1.53
0330	-1.56	.50	.16	.00	-.90
0400	-1.04	1.84	1.93	.00	2.73
0430	-.91	3.17	-.37	.00	1.90
0500	-.86	.87	-1.35	.00	-1.34
0530	-1.00	1.84	.80	.00	1.64
0600	-.39	1.74	2.04	.00	3.39
0630	.02	1.76	-.13	.00	1.65
0700	1.28	1.31	.87	.00	3.46
0730	2.66	1.11	.14	.00	3.92
0800	3.58	.95	-.59	.00	3.94
0830	3.87	1.16	.74	.00	5.77
0900	4.84	.88	.32	.00	6.04
0930	4.36	2.43	2.37	.00	9.16
1000	7.46	1.66	.41	.00	9.53
1030	10.61	1.10	.84	.00	12.55
1100	9.43	.64	.06	.00	10.14
1130	11.12	3.42	-.70	.00	13.84
1200	11.47	2.31	-.36	.00	13.42
1230	15.09	1.40	-.13	.00	16.36
1300	13.76	.67	2.39	.00	16.83
1330	22.01	2.81	3.47	.00	28.29
1400	12.12	3.47	-.58	.00	15.01
1430	12.65	.82	-.62	.00	12.85
1500	12.10	.60	.01	.00	12.71
1530	10.64	1.16	-.56	.00	11.24
1600	8.12	.82	.15	.00	9.09
1630	9.65	1.19	.30	.00	11.15
1700	6.10	1.86	.76	.00	8.71
1730	5.16	4.59	-.01	.00	9.74
1800	4.11	5.53	3.73	.00	13.37
1830	2.91	2.50	.84	.00	6.24
1900	1.90	2.31	-.30	.00	3.90
1930	1.41	2.56	2.60	.00	6.57
2000	.69	3.57	-2.72	.00	1.54
2030	.31	1.94	1.25	.00	3.50
2100	.56	1.60	.51	.00	2.68
2130	.87	2.07	1.35	.00	4.29
2200	1.13	2.21	.80	.00	4.14
2230	.95	2.20	2.41	.00	5.56
2300	1.10	2.77	2.14	.00	6.01
2330	.92	.70	.24	.00	1.87
TOTAL	192.29	83.41	27.46	.00	303.16
PER CENT	63.	28.	9.	0.	

AUGUST 29, 1967

CONTRIBUTION OF EACH COMPONENT OF THE HEAT BALANCE EQUATION IN LANGLEYS

TIME	QR	QA	QL	QP	QM
0000	-1.38	1.76	1.28	.00	1.67
0030	-1.06	1.05	.73	.00	.72
0100	-1.03	1.45	-.21	.00	.21
0130	-1.17	1.00	.01	.00	-.17
0200	-1.23	.61	-.73	.00	-1.34
0230	-1.10	.96	.41	.00	.27
0300	.85	.66	-.89	.00	.62
0330	.43	1.05	.69	.00	2.16
0400	-.69	.69	-.40	.00	-.41
0430	.78	3.23	.61	.00	4.02
0500	-1.49	3.27	.48	.00	2.26
0530	-1.27	3.46	.18	.00	2.37
0600	-1.02	4.22	-1.13	.00	2.07
0630	1.67	4.49	-.84	.00	5.32
0700	2.29	4.22	4.13	.00	10.64
0730	3.83	2.52	3.65	.00	10.00
0800	5.75	.00	.00	.00	5.75
0830	6.99	2.41	-.37	.00	9.03
0900	7.31	2.05	-.46	.00	8.90
0930	10.20	2.60	4.10	.00	16.89
1000	3.31	1.71	.44	.00	5.45
1030	5.44	2.02	1.79	.29	9.55
1100	12.17	2.82	1.90	.38	17.28
1130	4.47	-10.66	-.98	.00	-7.16
1200	7.14	5.24	4.62	.00	17.00
1230	15.25	1.60	.60	.00	17.45
1300	13.07	2.21	1.09	.00	16.37
1330	9.46	3.22	-.60	.00	12.06
1400	11.46	3.64	1.10	.00	16.20
1430	12.00	1.64	1.61	.00	15.25
1500	9.80	1.72	-1.03	.00	10.48
1530	5.33	1.67	-.50	.00	6.50
1600	7.97	1.97	.62	.20	10.76
1630	8.00	2.46	-.29	.00	10.17
1700	6.53	2.78	-1.90	.00	7.42
1730	4.60	3.48	-.82	.23	7.50
1800	2.63	1.41	.99	.00	5.03
1830	3.14	5.83	-1.10	.00	7.87
1900	2.16	6.81	.30	.00	9.26
1930	1.58	2.83	2.65	.00	7.06
2000	1.10	-2.23	22.47	.00	21.35
2030	1.30	6.01	4.01	.00	11.32
2100	.88	5.77	2.46	.00	9.11
2130	1.48	4.65	.45	.00	6.58
2200	1.47	4.11	3.23	.00	8.80
2230	1.37	2.65	2.39	.00	6.41
2300	1.18	3.68	1.22	.43	6.51
2330	1.17	3.64	3.62	.14	8.57
TOTAL	184.11	114.36	61.60	1.68	361.75
PER CENT	51.	32.	17.	0.	

REFERENCES

Adkins, C. J., 1958, The summer climate in the accumulation area of the Salmon Glacier: J. Glaciol., v. 3, no. 23, p. 195-206.

Ahlmann, H. W:son, 1948, Glaciological research on the North Atlantic coasts: Royal Geogr. Research Series, London, no. 1, 83 p.

Andrews, R. H., 1964, Meteorology and heat balance of the ablation area, White Glacier: Axel Heiberg Island Research Reports, Meteorology, no. 1, McGill Univ. Montreal, 107 p.

Battle, W. R. B., 1951, Glacier movement in north-east Greenland, 1949: J. Glaciol., v. 1, No. 10, p. 559-563.

Brecher, H., 1966, Surface velocity measurements on the Kaskawulsh Glacier, Yukon Territory, Canada: The Ohio State University, Inst. Polar Studies Report no. 21, 73 p.

Breed, C. B., Hosmer, G. L., and Bone, A. J., 1962, Higher Surveying, v. 2, J. Wiley and Sons, 543 p.

Bull, C., and Hardy, J. R., 1956, The determination of the thickness of a glacier from measurements of the value of gravity: J. Glaciol., v. 2, no. 20, p. 755-762.

Caisley, B., Lister, H., and Molyneaux, L., 1963, Measurement of profiles of wind speed, temperature, and vapor pressure near to the ground: I.U.G.G. General Assembly of Berkeley, Internatl. Assoc. Sci. Hydrol., Publication no. 61, p. 37-48.

Clark, D., 1951, Plane and Geodetic Surveying, v. 2, 4th ed, Constable, London, 582 p.

Corbató, C. E., 1965, Thickness and basal configuration of lower Blue Glacier, Washington, determined by gravimetry: J. Glaciol., v. 5, no. 41, p. 637-650.

Dobrin, M. B., 1960, Introduction to geophysical prospecting: McGraw-Hill, New York, 446 p.

Drake, L., 1965, Experiments on regelation of ice, unpublished Master's thesis, U.C.L.A.

Elliston, G. R., 1963, discussion, <u>in</u> Bulletin of the Internatl. Assoc. Sci. Hydrol., v. 3, Annee no. 2, p. 65-66.

Friese-Greene, T. W. and Pert, G. J., 1965, Velocity fluctuations of the Bersaekerbrae, East Greenland: J. Glaciol., v. 5, no. 41, p. 739-747.

Glen, J. W., 1952, Experiments on the deformation of ice: J. Glaciol., v. 2, no. 12, p. 111-114.

_________, 1955, The creep of polycrystalline ice: Proc. Roy. Soc. London, Ser. A, v. 228, no. 1175, p. 519-538.

Goldthwait, R. P., 1963, Dating the Little Ice Age in Glacier Bay, Alaska: Rept. of the International Geol. Congress. XXI Session, Norden, 1960, Part XXVII, p. 37-46.

_________, Loewe, F., Ugolini, F. C., Decker, H. F., Delong, D. M., Trautman, M. B., Good, E. E., Merrell, T. R. III, and Rudolph, E. D., 1966, Soil development and ecologic succession in a deglaciated area of Muir Inlet, southeast Alaska: The Ohio State Univ., Inst. Polar Studies Rept. no. 20.

Grainger, M. and Lister, H., 1966, Wind speed, stability and eddy viscosity over melting ice surfaces: J. Glaciol., v. 6, no. 43, p. 101-128.

Haefeli, R., 1963, Observations in ice tunnels and the flow law of ice: in Kingery, ed., Ice and Snow, M.I.T. Press, Cambridge, p. 162-186.

Hammer, S., 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4, no. 3, p. 184-194.

Haselton, G. M., 1966, Glacial geology of Muir Inlet, southeast Alaska: The Ohio State Univ., Inst. Polar Studies Rept. no. 18, 34 p.

Havens, J. M., 1964, Meteorology and heat balance of the accumulation area, McGill Ice Cap, summer, 1960: Axel Heiberg Research Rept., McGill Univ., Meteorology, no. 2, 87 p.

_________, Müller, F., and Wilmot, G. C., 1965, Comparative meteorological survey and a short-term heat balance study of the White Glacier, summer, 1962: Axel Heiberg Research Rept., McGill Univ., Meteorology, No. 4, 68 p.

Heiskanen, W. A., and Vening Meinesz, F. A., 1958, The earth and its gravity field: McGraw-Hill, New York, 470 p.

Kamb, W. B., and LaChapelle, E. R., 1964, Direct observation of the mechanism of glacier sliding over bedrock: J. Glaciol., v. 5, no. 38, p. 159-172.

Keeler, C. M., 1964, Relationship between climate, ablation, and run-off on the Sverdrup Glacier, 1963, Devon Island, N.W.T.: Arctic Institute of North America, Research Paper, no. 27, 80 p.

Klebelsberg, R. von, 1948-1949, Handbuch der Gletscherkunde und Glazialgeologie, 2 v., Springer-Verlag, Wien, 1028 p.

LaChapelle, E. R., 1959, Annual mass and energy exchange on the Blue Glacier: J. Geophys. Res., v. 64, no. 4, p. 443-449.

Lawrence, D. B., 1958, Glaciers and vegetation in southeastern Alaska: American Scientist, v. 46, p. 89-122.

Lliboutry, L., 1959, Une théorie du frottement du glacier sur son lit: Annales de Géophysique, Tom. 15, no. 2, p. 250-265.

_________, 1965, Traité de Glaciologie, v. 2, Masson, Paris, 1040 p.

_________, 1968, General theory of subglacial cavitation and sliding of temperate glaciers: J. Glaciol., v. 7, no. 49, p. 21-58.

McCall, J. G., 1952, The internal structure of a cirque glacier, report on the studies of englacial movements and temperatures: J. Glaciol., v. 2, no. 12, p. 122-132.

McKenzie, G. D., 1970, The glacial history of Adams Inlet, southeast Alaska: The Ohio State Univ., Inst. Polar Studies Rept. no. 25, 80 p.

McSaveney, M. J., and Gage, M., 1968, Ice flow measurements on Franz Josef Glacier, New Zealand, in 1966: New Zealand J. Geol. and Geophys., v. 11, no. 3, p. 564-592.

Marangunić, C., 1970, Effects of a landslide on Sherman Glacier, Alaska: The Ohio State Univ., Inst. Polar Studies Rept. no. 30, 120 p.

Marcus, M. G., 1964, Climate-Glacier Studies in the Juneau Ice Field Region, Alaska: Univ. Chicago, Dept. Geog. Res. Paper 88, 128 p.

Mathews, W. H., 1959, Vertical distribution of velocity in Salmon Glacier, British Columbia: J. Glaciol., v. 3, no. 26, p. 448-454.

Meier, M. F., 1960, Mode of flow of Saskatchewan Glacier, Alberta, Canada: U. S. Geol. Survey Prof. Paper 351, 70 p.

_________, 1962, Proposed definitions for glacier mass budget terms: J. Glaciol., v. 4, no. 33, p. 252-265.

_________, 1965, Comments on Paterson's paper, "Variations in velocity of Athabasca Glacier with time": J. Glaciol., v. 5, no. 41, p. 761-762.

Miller, D. J., Payne, T. G., and Gryc, G., 1959, Geology of possible petroleum provinces in Alaska, with an annotated bibliography by E. H. Cobb: U. S. Geol. Survey Bull. 1094, 131 p.

Millescamp, R., 1956a, Sur les directions d'ecoulement superficiel d'un tronçon de la Mer de Glace: Comptes Rendus Hebdomadaires des Séances de l'Académie de Sciences (Paris), Tom. 242, no. 3, p. 397-400.

________, 1956b, Sur la variation des vitesses d'ecoulement superficiel de la glace d'un tronçon de glacier: Comptes Rendus Hebdomadaires des Séances de l'Académie de Sciences (Paris), Tom. 242, no. 6, p. 803-806.

Nobles, L., 1960, Glaciological investigations, Nunatarssuaq Ice Ramp, Northwestern Greenland: SIPRE Tech. Rept. 66.

Nye, J. F., 1952, The mechanics of glacier flow: J. Glaciol., v. 2, no. 12, p. 82-93.

Østrem, G., and Stanley, A., 1966, Glacier Mass Balance Measurements, a manual for field work: Dept. Mines and Technical Surveys, Ottawa, Canada, 81 p.

Paterson, W. S. B., 1961, Movement of the Sefstrøms Gletscher, northeast Greenland: J. Glaciol., v. 3, no. 29, p. 844-849.

________, 1964, Variations in velocity of Athabasca Glacier with time: J. Glaciol., v. 5, no. 39, p. 277-285.

Price, R. J., 1964, Land forms produced by the wastage of the Casement Glacier, southeast Alaska: The Ohio State University, Inst. Polar Studies Rept. no. 9, 24 p.

Reid, H. F., 1896, Glacier Bay and its glaciers: U. S. Geol. Survey Annual Rept. 16, 1894-1895, pt. I, p. 415-461.

Reynolds, W. F., 1928, Manual of triangulation computation and adjustment, U. S. Coast and Geodetic Survey, Special Pub. 138, 242 p.

Schytt, V., 1962, Mass balance studies in Kebnekajse: J. Glaciol., v. 4, no. 33, p. 281-288.

Seligman, G., 1950, The specific gravity of ice: J. Glaciol., v. 1, no. 8, p. 442.

Shreve, R. L., 1962, Theory of performance of isothermal solid-nose hot points boring in temperate ice: J. Glaciol., v. 4, no. 32, p. 151-160.

Streten, N. A. and Wendler, G., 1968, The midsummer heat balance of an Alaskan maritime glacier: J. Glaciol., v. 7, no. 51, p. 431-440.

Taylor, L. D., 1962, Ice structures, Burroughs Glacier, southeast Alaska: The Ohio State Univ., Inst. Polar Studies Rept. no. 3, 110 p.

Theakstone, W. H., 1967, Basal sliding and movement near the margin of the glacier Østerdalsisen, Norway: J. Glaciol., v. 6, no. 48, p. 805-816.

Vallon, M., 1968, Errors in the determination of ablation using stakes: J. Glaciol., v. 7, no. 49, p.132-133.

Vancouver, G., 1801, A Voyage of Discovery, v. 5, p. 421-422, London.

Wallén, C. C., 1948, Glacial-meteorological investigations on the Kärsa Glacier in Swedish Lapland, 1942-48: Geografiska Annaler, v. 30, no. 3-4, p. 451-672.

Washburn, B. and Goldthwait, R. P., 1937, Movement of the South Crillon Glacier: Bull. Geol. Soc. America, v. 48, p. 1653-1663.

Weertman, J., 1957, On the sliding of glaciers: J. Glaciol., v. 3, no. 21, p. 33-38.

__________, 1962, Catastrophic glacier advances: Union Géodésique et Géophysique Internationale Assoc. Internationale d'Hydrologie Scientifique, Comm. des Neiges et Glaces. Colloque d'Obergurgl, September, 1962, p. 31-39.

__________, 1964, The theory of glacier sliding: J. Glaciol., v. 5, no. 39, p. 287-303.

__________, 1967, An examination of the Lliboutry theory of glacier sliding: J. Glaciol., v. 6, no. 46, p. 489-494.

Wright, C. F., 1887, The Muir Glacier: Amer. J. Sci., v. 33, p. 1-18.